United States Air Force
Scientific Advisory Board

Quick Look
Report on

Spectrum Management

SAB-TR-99-04

August 2000

Cleared for Open Publication

This report is a product of the United States Air Force Scientific Advisory Board Committee on **Spectrum Managemen**t. Statements, opinions, recommendations, and/or conclusions contained in this report are those of the Ad Hoc Committee and do not necessarily represent the official position of the USAF or the Department of Defense.

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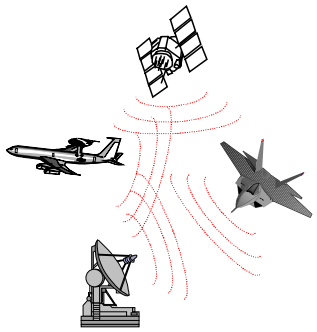
AFSAB SPECTRUM MANAGEMENT QUICK LOOK STUDY

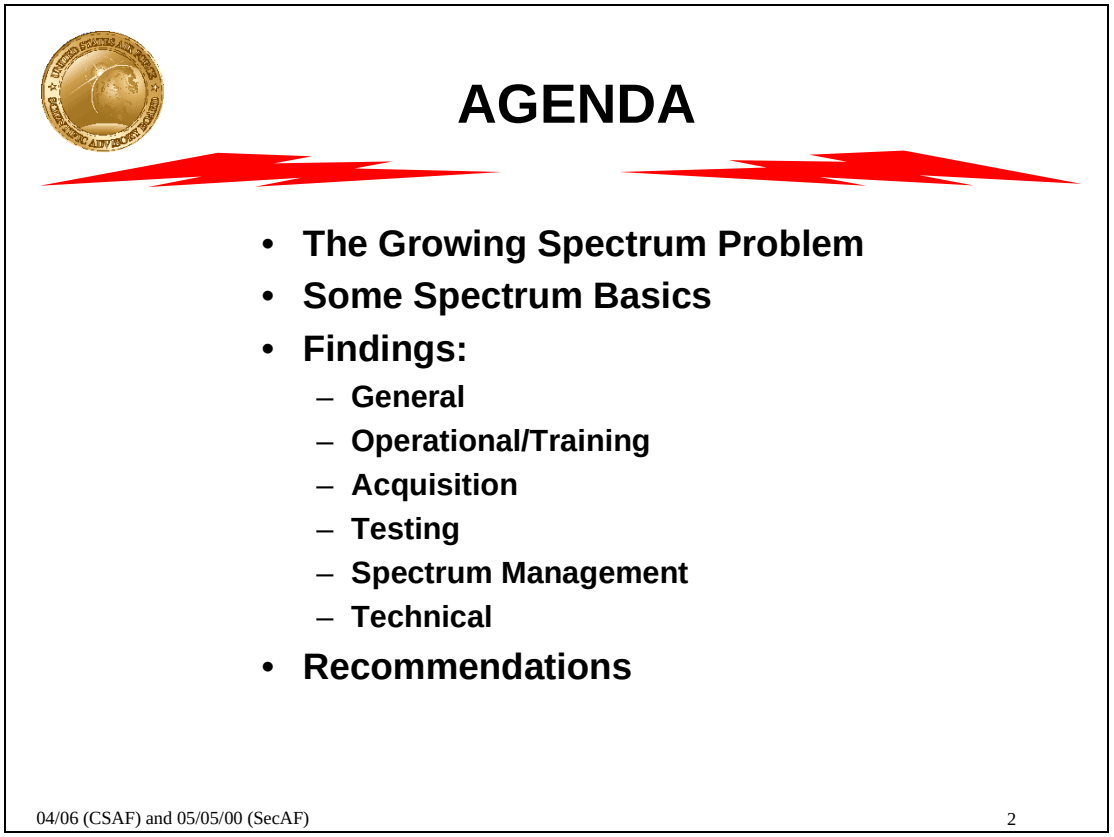


06 Apr 2000 Outbrief CSAF
05 May 2000 Outbrief SecAF

Spectrum Is As Important As Jet Fuel to National Security - and a LOT Scarcer!

ABSTRACT

A quick look study of the subject of spectrum management by a panel of the Air Force Scientific Advisory Board found that there are large and growing problems in this area which threaten major adverse operational and economic consequences for the DoD in general and the AF in particular. High value spectrum has become extremely crowded, and there have been multiple successful efforts to reallocate formerly military bands to commercial uses. The national and international processes by which spectrum is allocated are cumbersome. In addition, the processes are dominated by public and corporate interests that do not have to address national security concerns. The situation is such that the ability of the AF to train, conduct flight test, and even execute missions is already constrained, threatening both readiness and operational capability. The costs to modify or replace systems in response to spectrum losses are likely to reach tens of billions of dollars. The study panel consulted widely both with personnel responsible for representing the AF in the spectrum allocation process and with operational spectrum managers who try to support day-to-day operations with rapidly diminishing bandwidth. Findings were developed in such areas as operations and training, acquisition and testing, and improved technology for efficient bandwidth utilization. Both near term and long term recommendations were formulated. In the near term, the AF must better support its spectrum experts in defending remaining allocations and developing systems that comply with law and regulations while implementing bandwidth efficient designs. In the longer term, the AF should participate in a broad initiative to achieve the necessary level of DoD activity in the spectrum management arena, ultimately to reform legislation, to elevate awareness of the importance of spectrum access to national security, and to streamline both the US internal spectrum allocation machinery and its participation in international fora, especially the World Radio Conference (WRC).

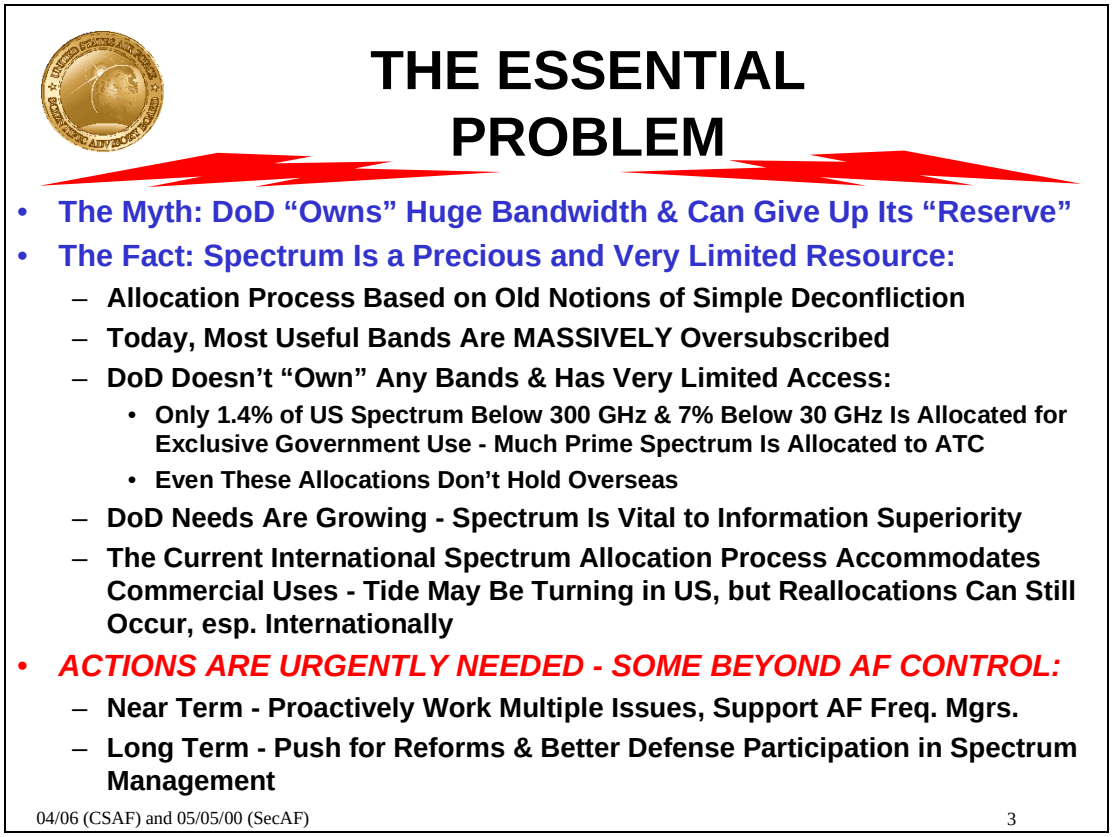


SECTION 1: INTRODUCTION

In 1999, the Air Force Scientific Advisory Board (AFSAB) was tasked to conduct a quick look study of spectrum management. This document presents the results of the effort in the form of an annotated outbrief. The Terms of Reference, which includes the background of the study, are attached as Annex A. The principal personnel who participated are listed in Annex B. Annex C defines various technical means of making more efficient use of available bandwidth.

The report is organized as follows:

- The first section introduces the overall problem and gives examples showing the growing seriousness of the situation.
- The next section provides a summary tutorial for audiences not familiar with spectrum management on both technical and administrative aspects.
- The Findings section presents the main results of the study, organized in subsections on general findings, operational/training aspects of spectrum access, system acquisition, system testing (especially flight test), the procedural and organizational dimension of spectrum management, and possible technical approaches to make better use of available bandwidth (sometimes called "bits per hertz.")
- Recommendations for actions which the AF can and should take and others, beyond direct AF control, where support for broader initiatives, including with Congress, should start immediately but will take years to bear fruit.



THE ESSENTIAL PROBLEM

The existing US spectrum management process and organizational structure belongs to a vanished age. The Communications Act of 1934 was written in a time when RF systems were relatively scarce, the spectrum seemed boundless, and the only perceived need was for a way to deconflict users who might otherwise accidentally settle on the same band and interfere with each other. The resulting structure, which will be described in detail in the second section of this report, relies on a political consensus mode of decision making which is typical of government functions in a democracy. It does not match very well the linear command relationships and analysis of alternatives that are familiar and comfortable to military leaders. The essential problem is that spectrum has, in fact, become a scarce and precious resource upon which both military systems and economic enterprises with hundreds of billions of dollars of revenue at stake are critically dependent. There is not enough bandwidth to go around and no way to create more, although means to get more efficient use of a given "chip" of spectrum do exist. Many spectral bands already have several users that can operate on the same legal "primary" basis and several more that operate on a "secondary" not-to-interfere basis with respect to the primary users. A very practical consequence of this scarcity has been a succession of moves, including auctions of spectrum to the highest bidder, to reallocate spectrum from military and other federal government to commercial uses, in part because many policy makers are ignorant of the consequences for national security.

Remaining primary spectrum allocations to military uses are already insufficient, while demands for communications connectivity and high bandwidth sensors are growing. The future of American military power depends on information dominance, and this, in turn, depends on availability of adequate spectrum. Contrary to the widely held perception, DoD does not "own" any spectrum, and exclusive allocations to Government uses now amount to only about 7% of the spectrum below 30 GHz. Even those allocations are only guaranteed within the US, and many of these bands are allocated to high priority functions such as air traffic control. At the same time, the national and international spectrum allocation process has

resulted in significant reallocations of spectrum from Government to commercial users, and more such moves are threatened. The AF, the other Services, and DoD as a whole must act urgently to keep the crisis from getting worse. As a practical matter of fact, DoD and the Services rely on a small cadre of trained professionals to cope with the crisis and have not devoted the attention and resources necessary to ensure military functions receive proper priority in spectrum decision bodies. In the near term, better support for Service spectrum managers and defenders, better system acquisition practices, and proactive work to head off crises are all essential. In the longer term, pragmatic steps are needed to improve Defense participation in the political spectrum process, to "work the system," and to move from the present situation of endless reaction to threatened loss of spectrum toward one of long range planning and proactive work to identify and defuse such threats.

While reform of the national spectrum management organization and process to better account for the current reality of intense, global competition for scarce bandwidth is probably in order, DoD and the Services must recognize that civil and commercial spectrum users think the present structure is appropriate. Altering it would require a completely new national spectrum paradigm, including new legislation and changes in national policy. Much of this is beyond the direct control of the AF, but the Study Panel recommends that the AF take the lead in promoting a much more effective Defense involvement in spectrum management and aggressive action to defend vital AF interests.

IS IT A CRISIS?

So many urgent problems beset the AF and the rest of DoD that the word "crisis" has been overused and has lost much of its significance. The Study Panel felt strongly that, if not yet a crisis of the first magnitude, spectrum access is a serious problem requiring vigorous and immediate corrective actions. While much more detail is given in the pages that follow, the dimensions of the situation can be illustrated as follows:

- It is commonly assumed that in a military contingency forces will do whatever is necessary to accomplish the mission, including ignoring peacetime restrictions on use of spectrum. Even if that is true, the inability to exercise sensors and communication systems in the modes and tactics that would be used in combat inhibits training. This can only partially be compensated for with simulators. It is likely to be especially troublesome in preparing for coalition operations.
- The loss of telemetry channels needed to conduct flight tests of new aircraft and radiation into civil RF systems critical for, e.g., air traffic control, national science objectives and the entertainment industry from new AF and DoD systems means that traditional approaches to flight test are becoming infeasible. Expensive workarounds such as testing at sites remote from normal ranges, substitution of anechoic chamber testing and simulation for normal flight test, and other undesirable alternatives may become the norm for emerging systems like the Joint Strike Fighter.
- The Link-16 band will have to coexist with the new L5 civil GPS signal (which will have primary allocation in the band) and other competition. Since this data link is the linchpin of future system-of-systems architecture for tactical operations, a further loss of capacity directly threatens the future operational effectiveness of air power.
- The essence of Air Expeditionary Forces is the ability to rapidly deploy, operate with minimum forward footprint, and provide CINCs with globally available options for dealing with the full

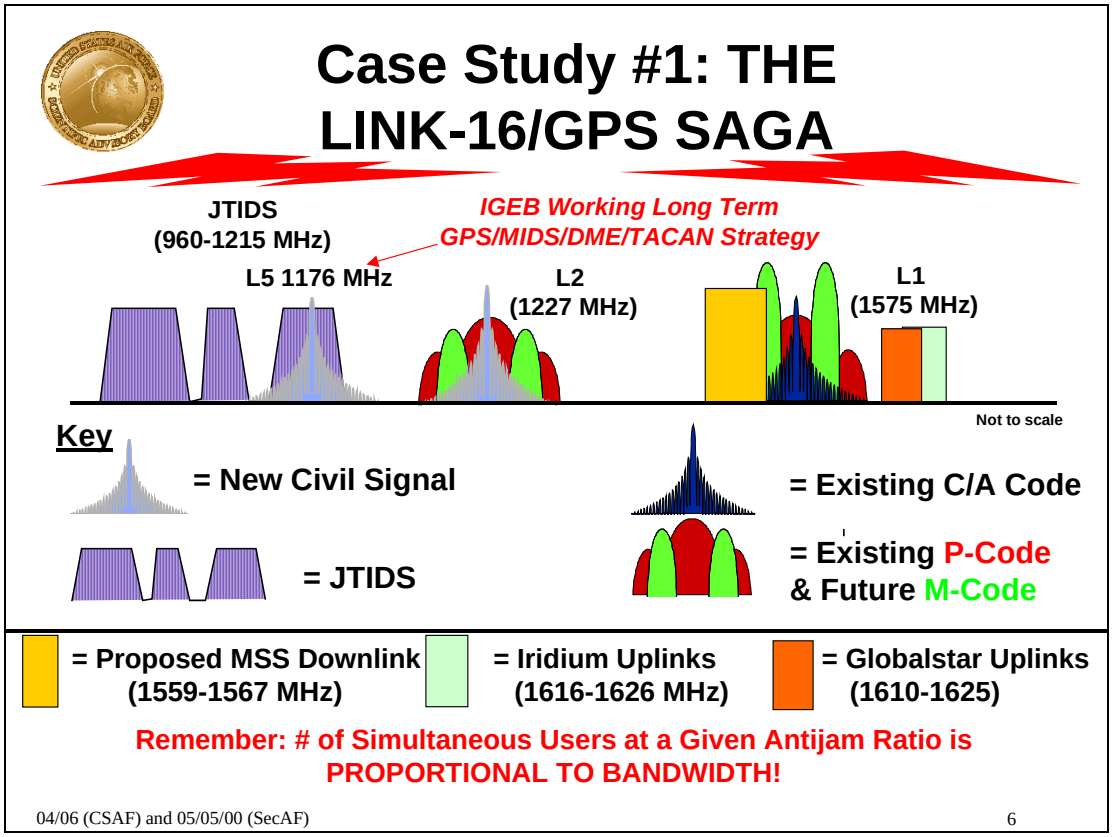
range of contingencies. The AEF concept relies on information dominance and robust support from CONUS to forward operating sites. Lack of communications for reachback, limitations on the full use of system capabilities, and similar consequences of loss of spectrum availability strike at the heart of expeditionary operations.

- The Balanced Budget Act of 1997 (BBA-97) mandated the reallocation of just 20 MHz of military spectrum, broken up into a number of relatively small chips, to commercial use. Conservative estimates of the impact to multiple Government agencies resulting from redesign or replacement of affected systems are in the range of $1B to $3B, with more than half of that falling on the AF. Fortunately, the FY 2000 Defense Authorization partially reversed the BBA-97 action, but any future spectrum reallocations will carry very large price tags.
- Several years ago, the Wing Commander at Tinker AFB was threatened with legal sanctions that could have involved a $20,000 fine against his personal funds because an AWACS conducting a normal training exercise interfered with a cable TV network's transmission of the 1994 Super Bowl game. Even interference that is inadvertent or due to shoddy equipment and poor practices by a commercial operator puts the military user legally at fault in spectrum where the military function is not the primary allocated use.

The aggregate of these consequences of vanishing spectrum availability for military functions is that the AF is already impaired in readiness and mission capability and faces staggering costs that, at best, do no more than maintain current system performance. Even more troubling is the very real prospect that more spectrum losses are likely and the reality that both the US and international spectrum allocation processes have favored commercial over national security interests.

WE MAY BE ON THE BRINK OF BIG PROBLEMS!

The AF and other Services are being pushed down a path of spectrum availability that has narrowed dramatically in less than a decade, and powerful forces continue to chip away at what remains. The next step could well be over the cliff. To date, no operations have failed or been cancelled simply because of lack of spectrum access. Nevertheless, the Study Panel is convinced that this is a major and growing problem. The next few charts provide concrete examples.

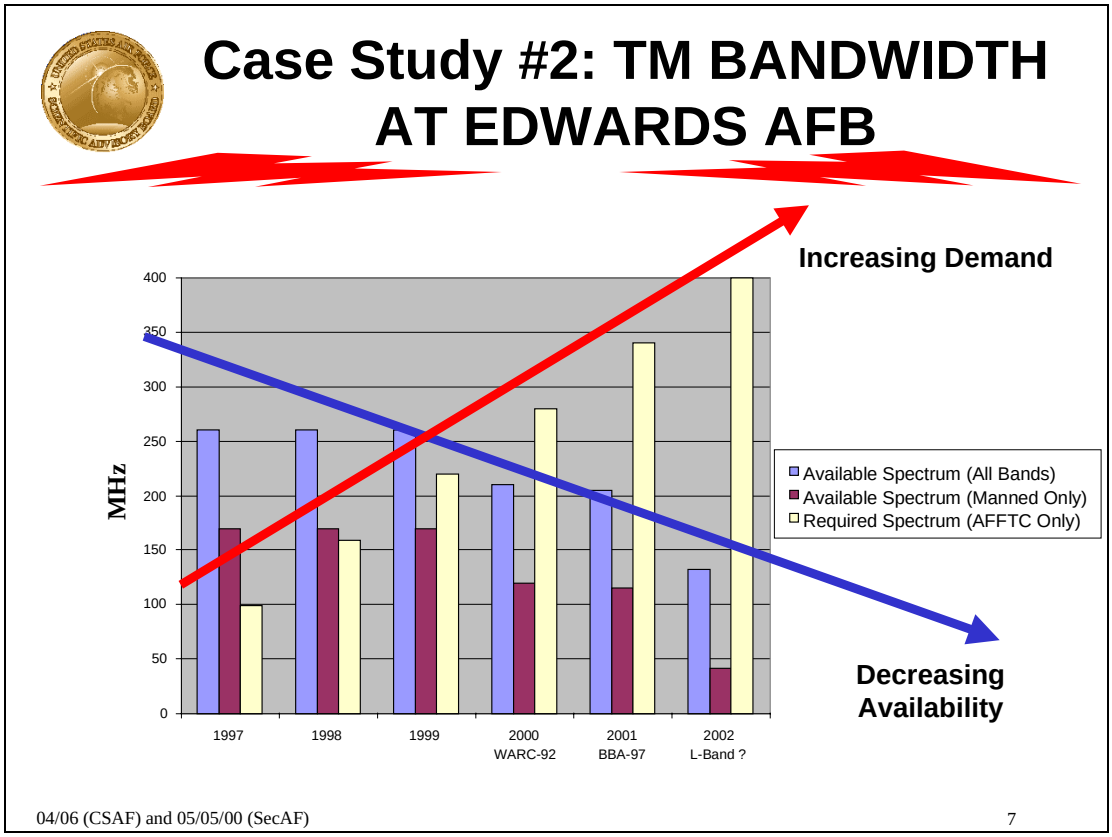


Case Study #1: THE LINK-16/GPS SAGA

A design decision made many years ago placed Link-16 (TADIL-J, JTIDS) in L-Band (960-1215 MHz). For reasons explained later in more detail, this is prime spectrum for mobile radiocommunications and navigation functions. Link-16 is not the primary allocated function and thus must operate on a non-interference basis with aeronautical radionavigation. Link-16 uses a variety of coding and frequency hopping techniques to achieve secure, jam-resistant connectivity. At any desired antijam ratio, the number of simultaneous users is directly proportional to the available hopping frequencies and thus to the allocated bandwidth. Link-16 is critical to tactical air operations, both for coordination among weapon system and sensor platforms during missions and as the means of distributing information that would otherwise require every aircraft to have satellite communications and other equipment.

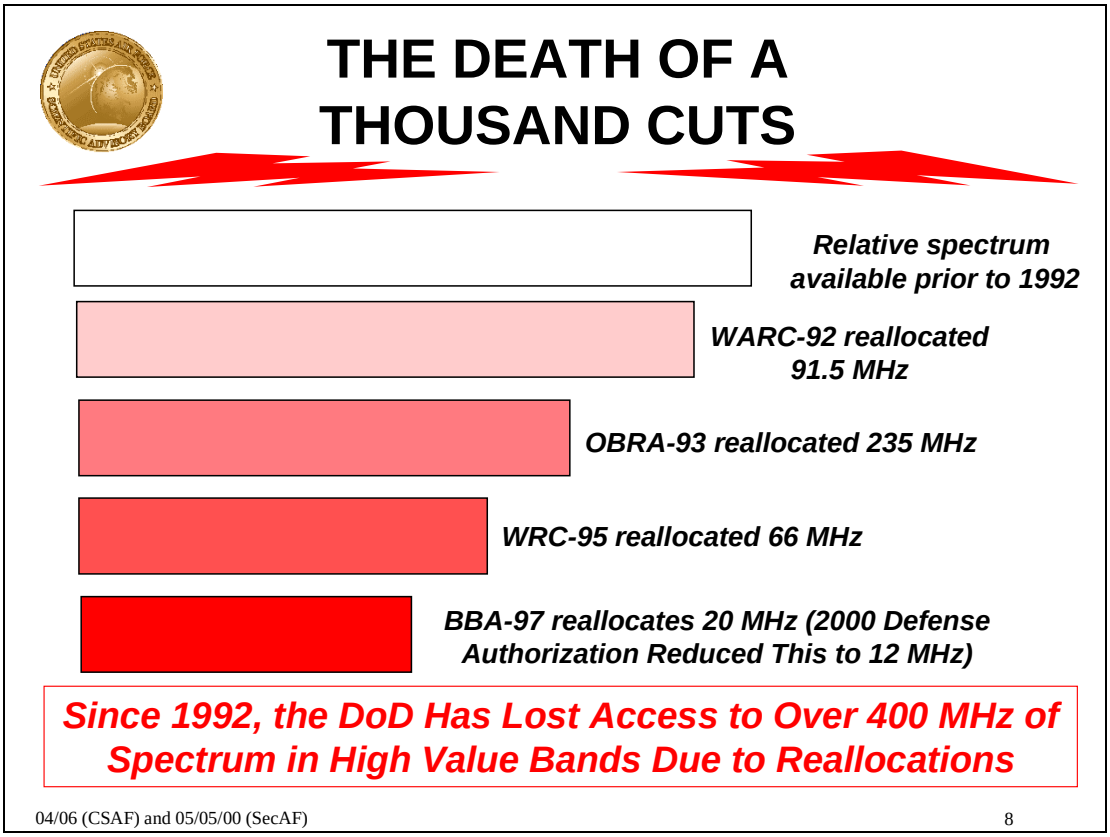
Link-16 spectrum has been and remains under attack. The recent decision to place a third GPS signal, referred to as L5 and intended to give civil users high accuracy service, in the middle of this same upper Link-16 band threatens a serious loss of capacity since the GPS service will be used for aircraft navigation and thus have priority over a military data link. The Interagency GPS Executive Board (IGEB) has proposed a compromise involving changes to ground-based radio navigation system frequencies. Block II F GPS satellites will have higher transmitted power, including a proposed high gain spot beam for greatly improved jam resistance in specific areas and a more powerful precision military code on the existing L1 and L2 signals. These improvements are scheduled to begin to appear in about 2007 as current satellites are replaced and will help maintain robust GPS service to friendly forces. However, unless it can be proven that Link-16 does not interfere with the L5 signal, DoD may face a choice between a loss of capacity in a system that is already considered “fragile” in its ability to support large scale operations or huge costs to move to a higher band, perhaps millimeter wave, and to modify or replace existing terminals.

GPS itself is not safe from attack. A crisis was created at the most recent World Radio Conference (WRC) by an attempt to put a new Mobile Subscriber Service (MSS) downlink on the skirts of the GPS L1 signal where it would have interfered with the military high precision P-Code. Other civil satellite links are uncomfortably close to L1, although Iridium is apparently going away. While the attempt to reallocate the 1559-1567 MHz spectrum chip for MSS seems to have abated somewhat, it will be discussed at WRC-2000, and there is no assurance that it can again be defeated. In short, two of the most vital RF functions on which the AF is increasingly reliant are in very real danger of being degraded or lost.



Case Study #2 TELEMETRY BANDWIDTH AT EDWARDS AFB

Flight test ranges such as the Air Force Flight Test Center at Edwards AFB rely on telemetry to complement on-board data recording, test pilot reports, and ground-based instrumentation in providing a complete data capture capability. TM demands increase as unmanned air vehicles and missiles, as well as systems of increasing sophistication, become increasingly prominent in flight test operations. However, a large fraction of the historically available TM spectrum has already been lost, and a major effort was required to modify a proposed commercial satellite-based direct broadcast music service which, for a time, appeared to threaten the remainder. Fortunately, the most recent proposal by this commercial operator, WorldSpace, indicates that their beam can be pointed to avoid AFFTC airspace. An analysis by the Edwards frequency management organization shows that in 1999 the demand and availability curves cross, and, in fact, AFFTC has identified a two-ship F-22 test profile for which the requested TM channels cannot be provided without a reduction in the required amount of data. Technical means such as bandwidth compression may help alleviate the problem, but will force costly changes to existing TM equipment. As systems such as the Unmanned Combat Air Vehicle (UCAV) and Joint Strike Fighter (JSF) enter the test phase of their development, lack of adequate TM bandwidth threatens to create serious cost and schedule impacts.



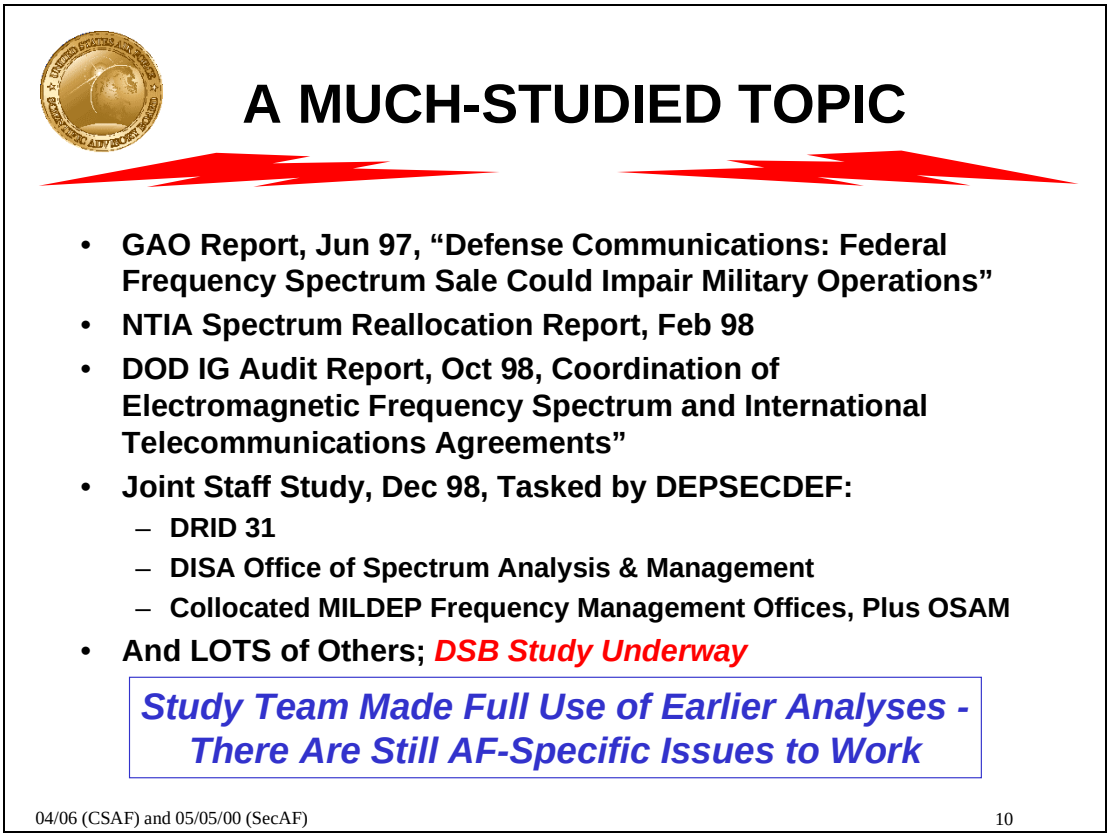
THE DEATH OF A THOUSAND CUTS

A succession of Congressional actions and WRC decisions just in the decade of the 90's has cost DoD access to over 400 MHz of spectrum. Moreover, the bands involved were at the most desirable frequencies for key functions like data links, instrumentation and communications, meaning that relocating these functions to higher, less crowded bands, assuming such exist, entails both the cost of new or redesigned equipment and compromises in performance. While each of these actions, taken in isolation, might have appeared manageable, the cumulative effect is disastrous. Although the Fiscal Year 2000 Defense Authorization Bill reverses the trend somewhat and suggest that Congress is becoming aware of the security implications of spectrum reallocation, the precedents that have been established mean that close attention to spectrum access for Defense users will be vital for the foreseeable future.

A LOT OF STAKEHOLDERS

Part of the reason for the fragmented nature of spectrum management, even within the US Government, is the number of organizations with vital interests in maintaining or expanding their spectrum access. Although this quick look study was smaller in scope than a full summer study, the Study Panel attempted to hear from as broad and representative a sample of stakeholders as possible, as shown by the organizations listed in blue italics in the chart.

The AF does a fine job of ensuring that its voice is heard in the national spectrum debate and coordinated with other DoD interests. The next section of the report expands on the issue of multiple, often uncoordinated or even competing non-military, voices in the ongoing debate over spectrum use.



A MUCH STUDIED TOPIC

Various aspects of this issue have been the subject of multiple analyses and directives in recent years. A 1997 General Accounting Office report summarized the growing crisis and highlighted several key aspects. These include the deleterious effects of the absence of standards for receiver selectivity in commercial equipment and the impact of reallocations of military spectrum to commercial use. The report recommended a moratorium on spectrum auctions until the national security impacts could be assessed and dealt with.

The NTIA Spectrum Reallocation Report responding to the BBA-97 Congressional mandate described the reallocation actions to be taken and attempted to quantify the economic impact. The report arrived at an extremely conservative estimate of $1.1B affecting 10 different agencies. Of that, $520M fell on the Air Force. Later analyses have suggested that this estimate may be too low by as much as a factor of three.

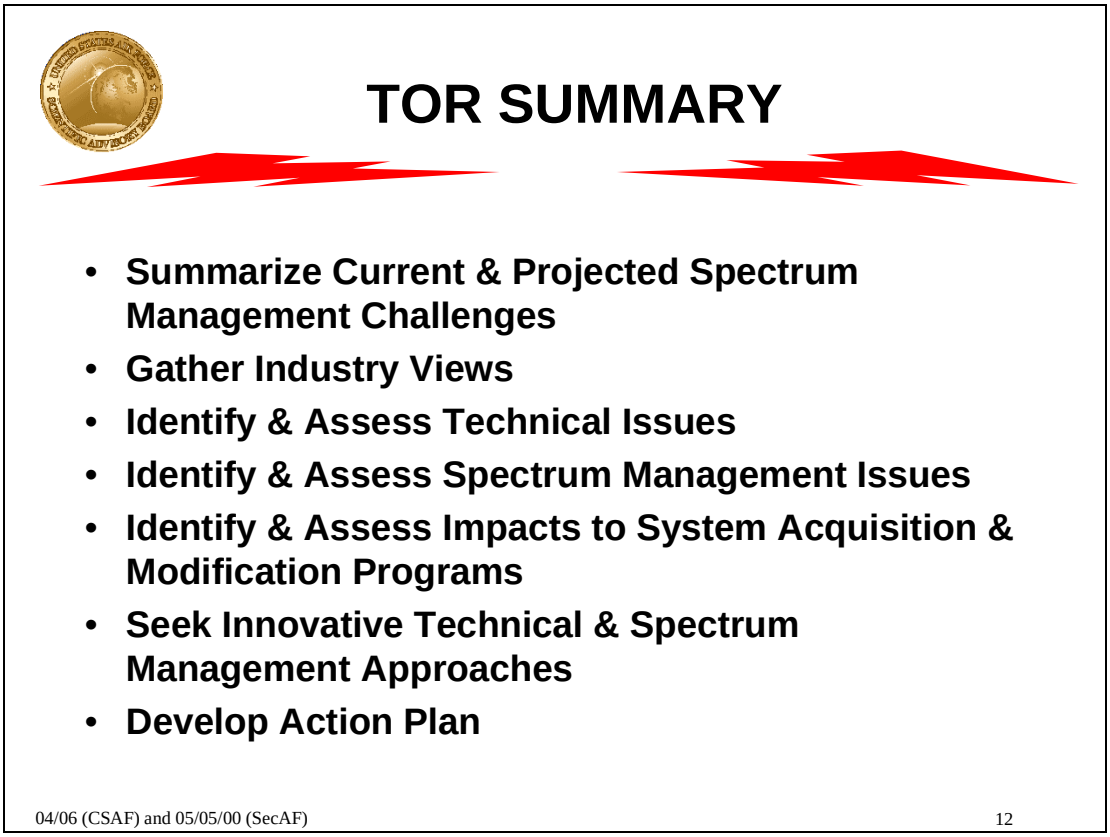
In October, 1998, the DoD Inspector General issued an audit report critical of the lack of spectrum approval prior to fielding telecommunications equipment in the Department.

Largely in response to the IG report, a Joint Staff Study tasked by the Deputy Secretary of Defense led to the issuance of Defense Reorganization Initiative Directive 31 (DRID 31). This focused on the need for better DoD coordination and led to the establishment within the Defense Information Systems Agency of a new Office of Spectrum Analysis and Management (OSAM). It also sought to realign and improve overall DoD Spectrum Management activities. Steps as basic as collocating the Service spectrum management organizations and OSAM have paid large dividends in improving DoD's ability to work problems and defend military spectrum access.

While it appears that this area has been studied exhaustively, the cited analyses concentrate on national and DoD level organizations and processes. The Study Panel found that there are AF-specific actions which should be taken. Furthermore, the Panel believes that the AF should take a leadership role in mustering joint commitment and action to attack spectrum matters beyond its immediate control. The Panel made full use of the results of earlier studies, but found that an AF-centric look at the problem is warranted.

SO WHY ANOTHER SPECTRUM STUDY?

The immediate origins of this Quick Look study trace back to a finding of the 1998 Summer Study on "A Space Roadmap for the 21st Century Aerospace Force." In looking at the migration of surveillance and targeting radar to orbit, that study identified frequency allocation as a serious problem needing to be worked at the earliest opportunity. Other spectrum issues like the attack on GPS at the 1997 World Radio Conference (WRC 97) were also identified. The space study's recommendation in this area led to contact with the Air Force Frequency Management Agency (AFFMA) and ultimately to the conclusion that a focused look at the overall spectrum situation was needed and within the competence of the AFSAB. These preliminary conversations highlighted areas like those listed in Chart 11 as important matters for a Quick Look study to examine.

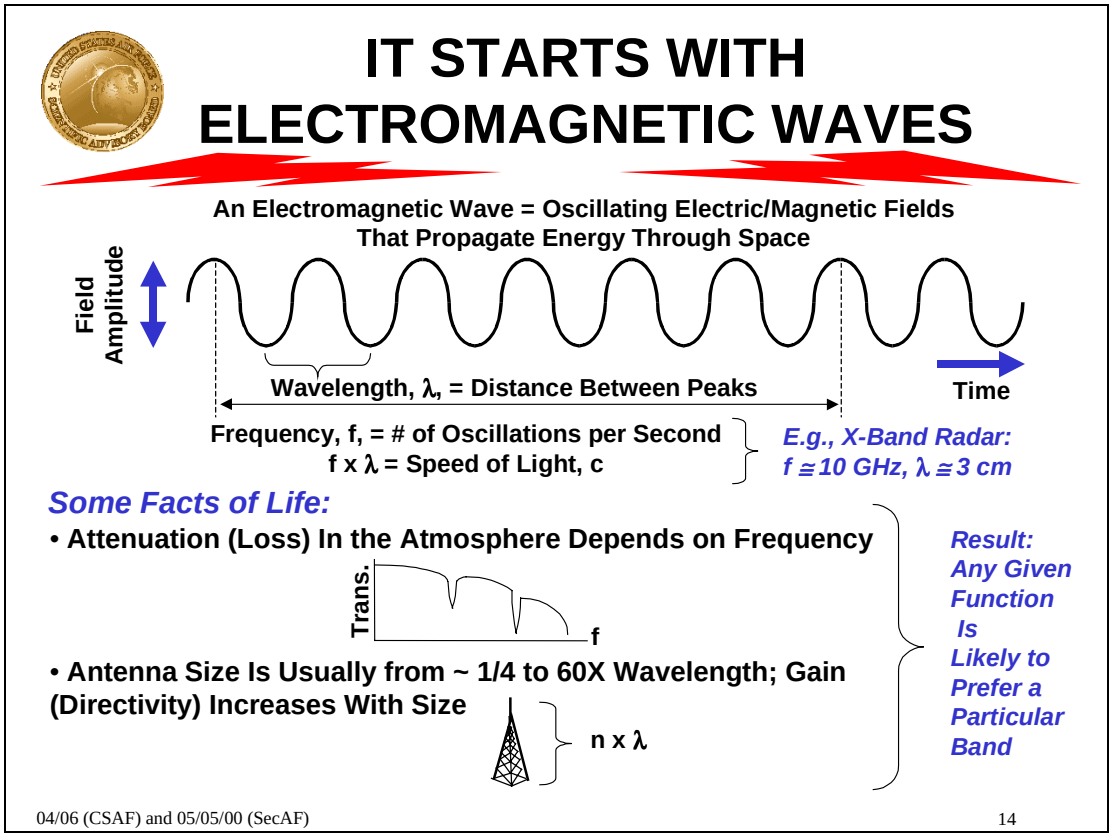


TERMS OF REFERENCE (TOR) SUMMARY

The TOR, Annex A, calls for the study to accomplish the activities summarized in Chart 12.

SECTION 2: SOME SPECTRUM BASICS

Spectrum management inescapably involves technical, administrative, and operational aspects. Any meaningful discussion demands a basic familiarity with electromagnetic signals, the terminology of spectrum management, and they ways in which the characteristics of systems and equipment vary with frequency. This section of the report provides a high-level tutorial on spectrum and on the ways in which spectrum management is currently carried out.



IT STARTS WITH ELECTROMAGNETIC WAVES

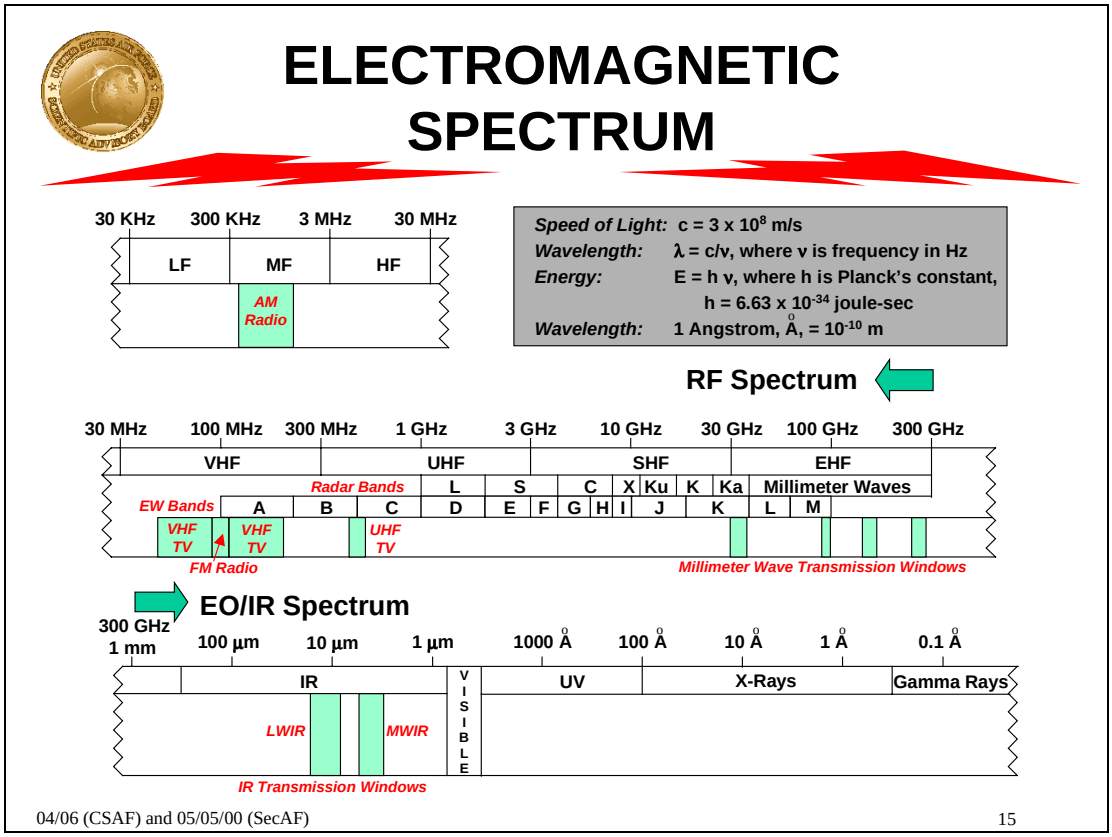
Radio frequency (RF) waves, electro-optical (EO) waves, X-rays and all other forms of electromagnetic (EM) waves are energy that propagates in the form of alternating (oscillating) electric and magnetic fields. The two alternating fields go together and sustain each other. Whether or not such waves can be seen by the human eye, can penetrate solid materials, can be reflected off objects, and so forth is largely determined by their frequency, i.e., by the spectral region in which they lie. One of the keys to understanding spectrum management is that, while the equations that govern electromagnetism don't depend on frequency, e.g., all such waves travel at the speed of light, the practical aspects of building systems that use such waves vary dramatically. All spectrum is not created equal, and the competition for the frequency bands that are easiest to use is intense.

Of the many parameters that describe an EM wave, the two most important are frequency and wavelength. Others, such as polarization, are important to engineers and frequency managers, but are beyond the scope of this overview. If an observer standing in one place could count the number of oscillations per second of a wave as it went by, he or she would have measured the frequency. If the wave could be frozen ("photographed") at an instant in time, the distance in space between two peaks in the pattern of electric or magnetic field amplitude is the wavelength. By basic physics, the frequency times the wavelength is the velocity, and thus each can be calculated from the other by dividing into the value of the speed of light. The most common symbols for these three are f or the Greek letter ν for frequency, the Greek letter λ for wavelength, and c for the speed of light. To give an example with which most AF people are familiar, a typical fighter radar operates in what is called X-band at a frequency of around 10 GHz (10 billion cycles per second); the corresponding wavelength is around 3 cm.

The spectrum is described and managed by labeling ranges of frequency or wavelength and by allocating specific bands (or sub-bands or "chips") to particular uses. For example, the 8.5 – 10.0 GHz band has a primary allocation to radiolocation, and is the most common frequency range for airborne tactical radars.

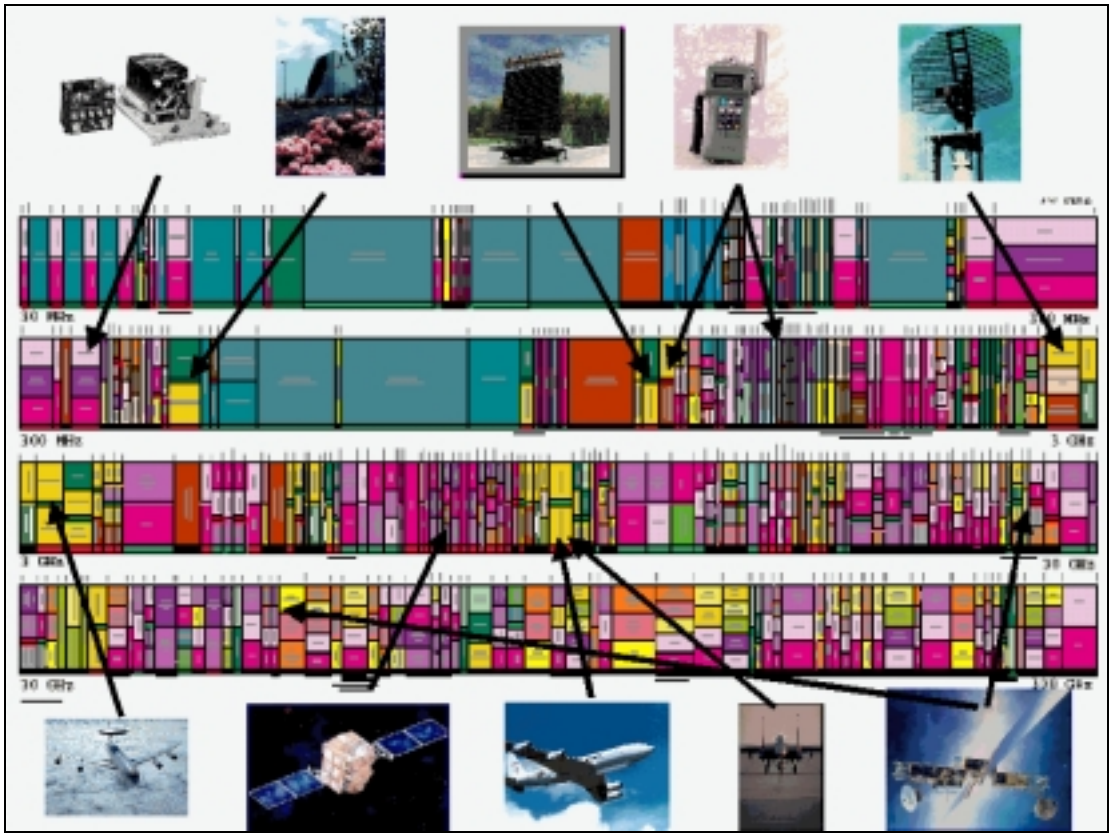
Three important aspects of spectrum for purposes of understanding competition for its use are attenuation, antenna size, and ability to propagate signals beyond the horizon. Below about 10 GHz, the loss of strength in an EM wave due to absorption of energy by the atmosphere is relatively minor. However, at higher frequencies, this attenuation (or its inverse, transmission) varies widely with frequency. Eventually, in the millimeter wave and infrared (IR) bands, there are only a few narrow "windows" in which it is feasible to propagate signals through the atmosphere. (None of this matters in space.) As sketched in the lower half of Chart 14, the spectrum above about 20 GHz is characterized by transmission windows alternating with regions of high attenuation. For example, millimeter wave missile seekers tend to operate at around 34 or 96 GHz to take advantage of two fairly narrow windows. The point is that one approach to dealing with spectrum crowding, namely, moving functions to higher frequency bands, is severely constrained by the need to operate in suitable windows.

Both the ability of an antenna to efficiently radiate energy from a transmitter and the ability to generate narrow beams, e.g., for a radar, depend heavily on antenna size. More precisely, the relationship between antenna dimension and the wavelength of the signals to be radiated is key to determining the antenna "pattern," i.e., the directions in which it radiates or receives effectively. Low gain antennas, which radiate in many or all directions, tend to have dimensions of ¼ or ½ of a wavelength, while a high gain antenna to generate a pencil beam for a radar might have a diameter of tens wavelengths. Thus, the size of the antenna for a given pattern goes down as the frequency goes up. When it comes to integrating a suitable antenna into an airframe or to designing a handheld receiver able to detect weak signals from satellites, antenna size, and thus operating frequency, are major considerations. Finally, it may be important in a given application that only fairly low RF frequencies (HF band and below) can follow the curve of the earth. Higher frequencies are limited to line-of-sight (LOS) propagation. A recent example of this involves the restrictions of LOS command links on the operation of unmanned air vehicles (UAVs), prompting the use of satellite relays.



ELECTROMAGNETIC SPECTRUM

Chart 15 is included mainly for reference. It summarizes the most important labeling schemes for various spectral bands, shows where some commercial operations such as FM radio and broadcast TV fall (Note: they are at different frequencies in other parts of the world!), and where major millimeter wave and IR windows lie. Note that, for convenience, spectrum below 300 GHz is labeled by frequency and called the RF spectrum, while above 300 GHz the labels are in terms of wavelength, and the spectrum is dubbed EO/IR. To avoid the confusion of multiple, overlapping band labeling schemes, spectrum professionals prefer to define a given region precisely by its range of frequencies or wavelengths.



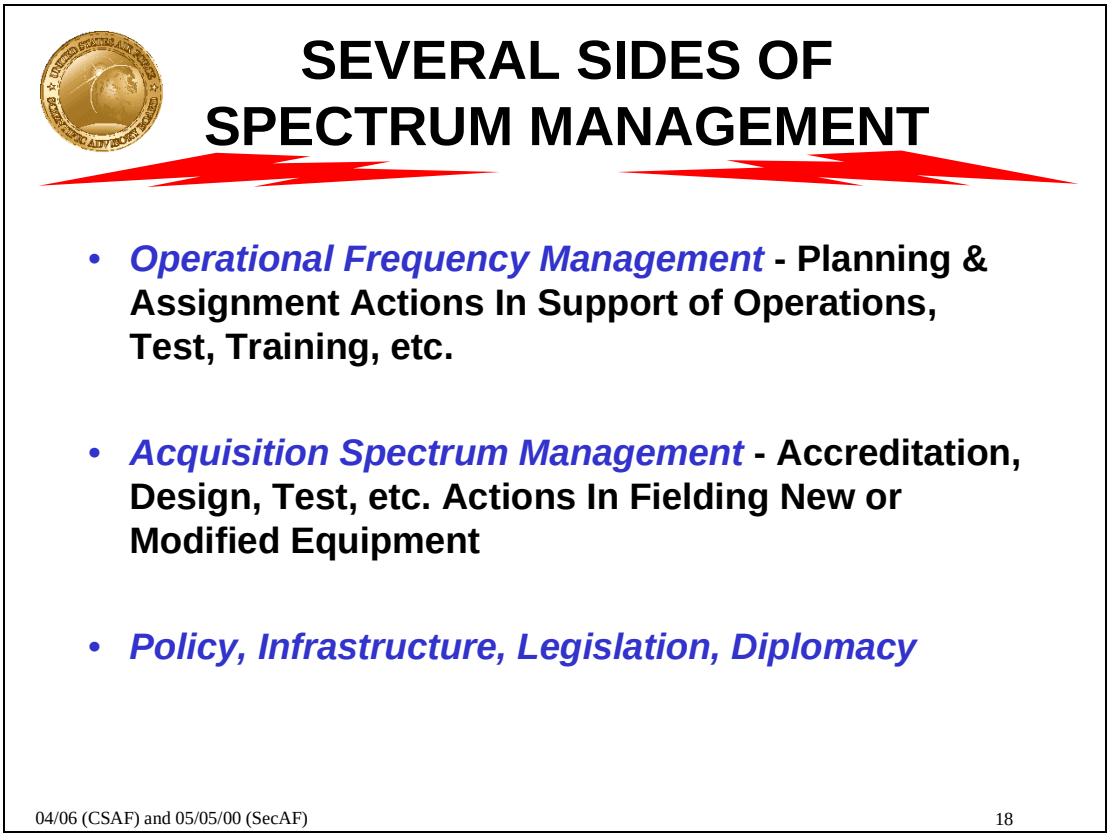
SPECTRUM CHART

Chart 16 highlights the complexity of the spectrum management challenge. The following points are important:

- The spectrum is carved up into very small chips, and even so, there are commonly both one or more primary allocations and as many as three secondary allocations, with the latter authorized to use the band only on the basis of noninterference with the primary.
- DoD systems use frequencies throughout the spectrum, for reasons summarized earlier in this report. In the past, DoD had adequate primary allocations for the functions it needed. Today, DoD has few primary allocations, and many systems critical to both peacetime and wartime operations must share spectrum on a co-equal basis with civil systems or have secondary status and are subject to the noninterference limitation.
- AF spectrum access outside the US is affected by national sovereignty issues and subject to obtaining host nation spectrum approvals. By international law, any country can allow or forbid any spectrum use within its borders. There is no such thing as an internationally recognized military spectrum allocation. For example, even NATO's UHF radio frequency allocation is neither global nor guaranteed. Moreover, countries can and do revoke earlier authorizations, sometimes for political purposes.

SOME KEY TERMS

This and the next chart define some basic spectrum management terminology. For example, the difference between "allocation" and "assignment" is fundamental and can be confusing. To the acquisition community, the critical process is "certification," by which a given system or equipment is cleared to operate in a band where an appropriate allocation has been made. Many of this study's findings and recommendations revolve around the way spectrum is treated in acquisition programs. Certification is accomplished through a DD Form 1494, which becomes the paperwork vehicle for what is called the JF-12 process, about which more detail is given later in this report.



SEVERAL SIDES OF SPECTRUM MANAGEMENT

To clear up one final common point of confusion, Chart 18 distinguishes three basic aspects of spectrum management.

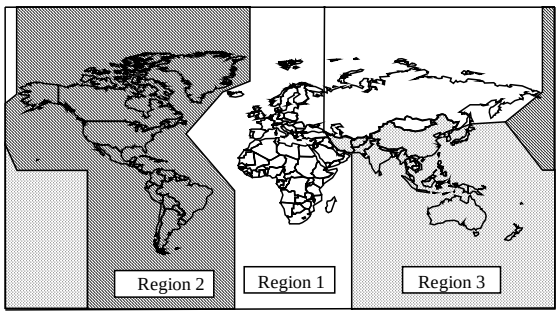
- Communications squadrons and joint staffs have skilled personnel who work the day-to-day process of planning spectrum use, assigning frequencies to users, and providing other services in support of operations. Their focus is on ASSIGNMENT.
- Acquisition organizations and program offices have (or are supposed to have) personnel with the skills to deal with design trades, test requirements, documentation, and other aspects of obtaining ACCREDITATION for new or modified equipment.
- MILDEP spectrum organizations like AFFMA and the other MILDEP FMOs, in addition to overall coordination of spectrum matters, deal with the critical issue of spectrum ALLOCATION and thus with the associated policy questions. OASD/C3I and OSAM deal with overall DoD spectrum diplomacy and long range planning, with the strong support and involvement of the Services.

All of these organizations are short of personnel and resources, and all are essential to AF and DoD access to spectrum.

FREQUENCY ALLOCATIONS VARY BY REGION & COUNTRY

ITU Radio Regulations

Chart of Regions as Defined in Table of Frequency Allocations



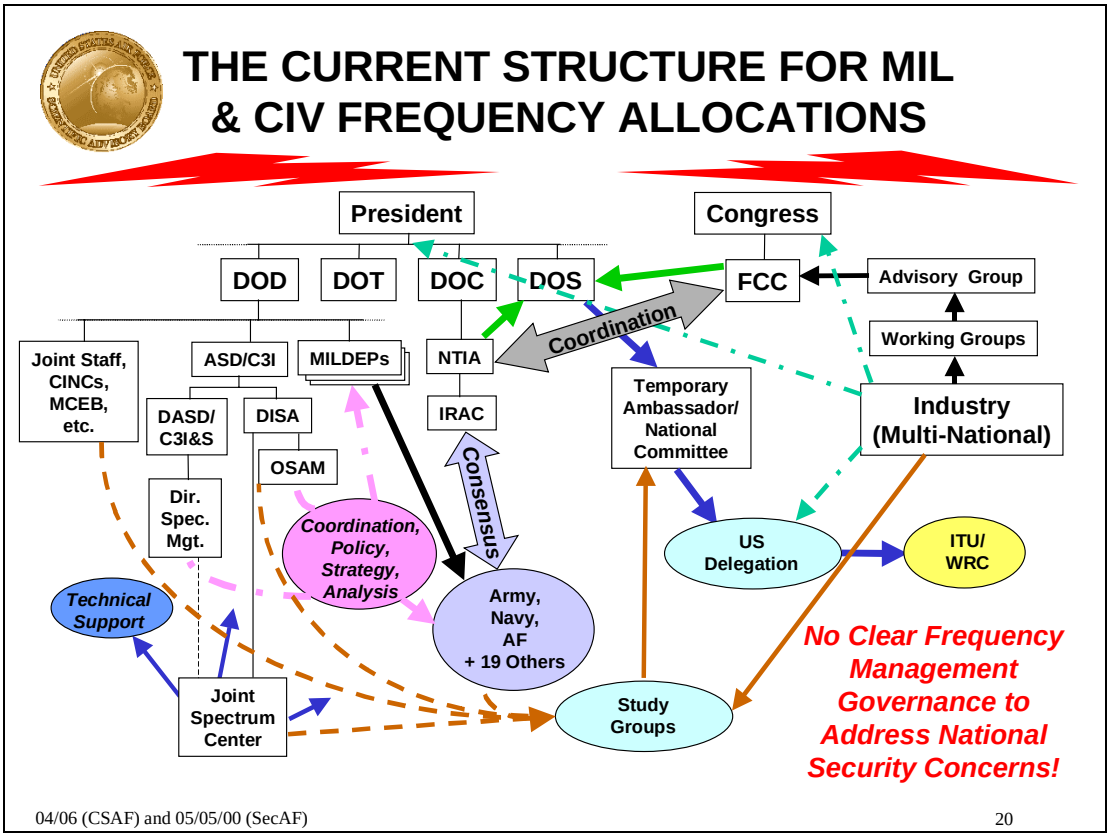
ITU Regions 1, 2, and 3

"Exclusive Government" Spectrum Use Is ONLY In the US!

04/06 (CSAF) and 05/05/00 (SecAF) 19

FREQUENCY ALLOCATIONS VARY BY REGION AND COUNTRY

The International Communications Union (ITU) allocates frequencies in three regions of the world as shown in Chart 19. However, as noted earlier, even within these regions, nations can allow or disallow any spectrum use. The term "Exclusive Federal" spectrum is meaningless outside the borders of the US.



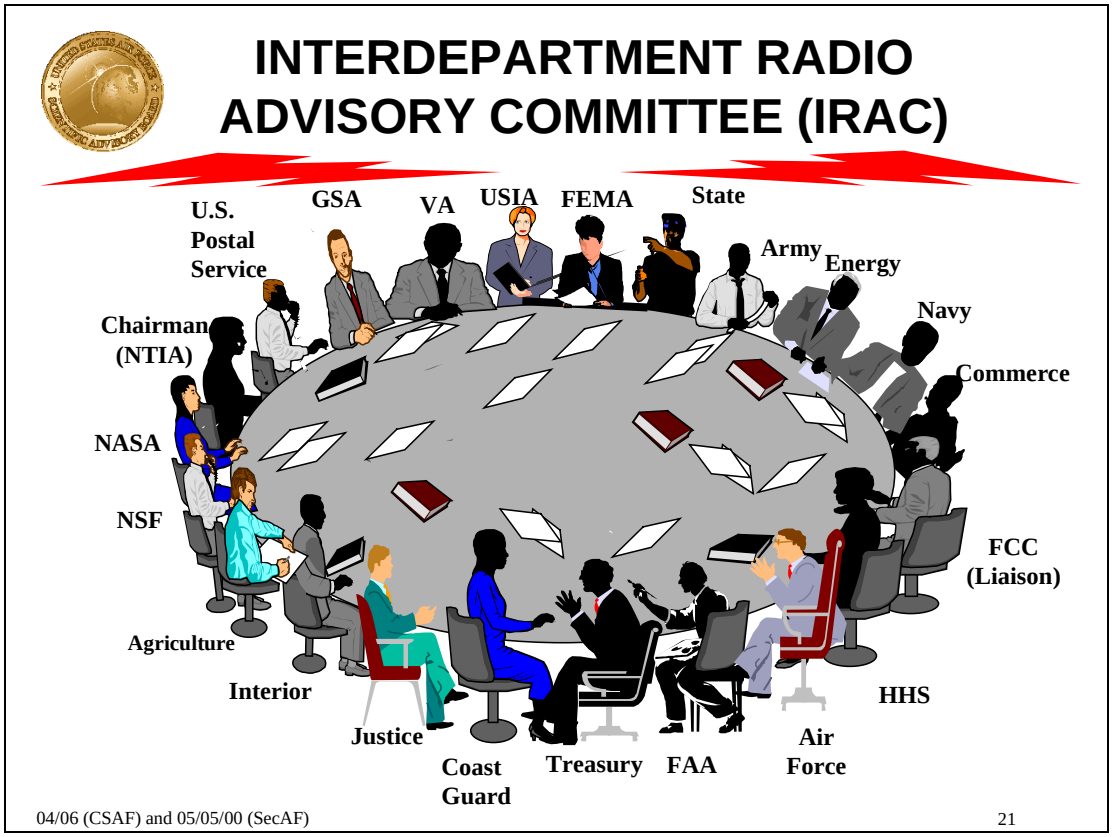
THE CURRENT STRUCTURE FOR MILITARY AND CIVIL FREQUENCY ALLOCATIONS

Chart 20 attempts to capture on one page the organization and process by which frequency allocations are worked. Under current law, the Federal Communications Commission, which reports to Congress, is responsible for non-government frequency management (including state and local government users), and the National Telecommunications and Information Administration (NTIA), which reports to the Department of Commerce in the Executive Branch, does the same for government frequency management. There is no mechanism other than coordination for resolving conflicts between the two. Under NTIA, the Interdepartmental Radio Advisory Committee with 22 members is charged with coordinating government spectrum. The next chart shows the membership. DoD is represented by the three MILDEPs. AFFMA articulates and defends AF spectrum interests at this national level arena. Within DoD, the ASD/C^3I staff has overall spectrum management responsibility. The Director of Spectrum Management reports to the DASD/C^3I&S, while the Defense Information Systems Agency (DISA) owns both the Joint Spectrum Center (JSC) and the newly created Office of Spectrum Analysis and Management (OSAM). JSC takes its day-to-day direction from the Director, DISA. However, these organizations do not sit on the IRAC and must work through policy and coordination channels to the Military Departments. Operational spectrum management, including planning and requirements, come from the warfighter community, including the Joint Staff, regional CINCs, the Military Communications and Electronics Board (MCEB), and so forth. The JSC provides technical support, largely on a fee-for-service basis, to anyone in DoD, and, with ASD/C3I concurrence, to the private sector.

When the time comes to prepare for a WRC, at which DoD spectrum access must be defended against the rest of the world, the FCC and NTIA are supposed to work with the Department of State to prepare US positions. An ambassador, usually a temporary appointee and with no assured background in spectrum

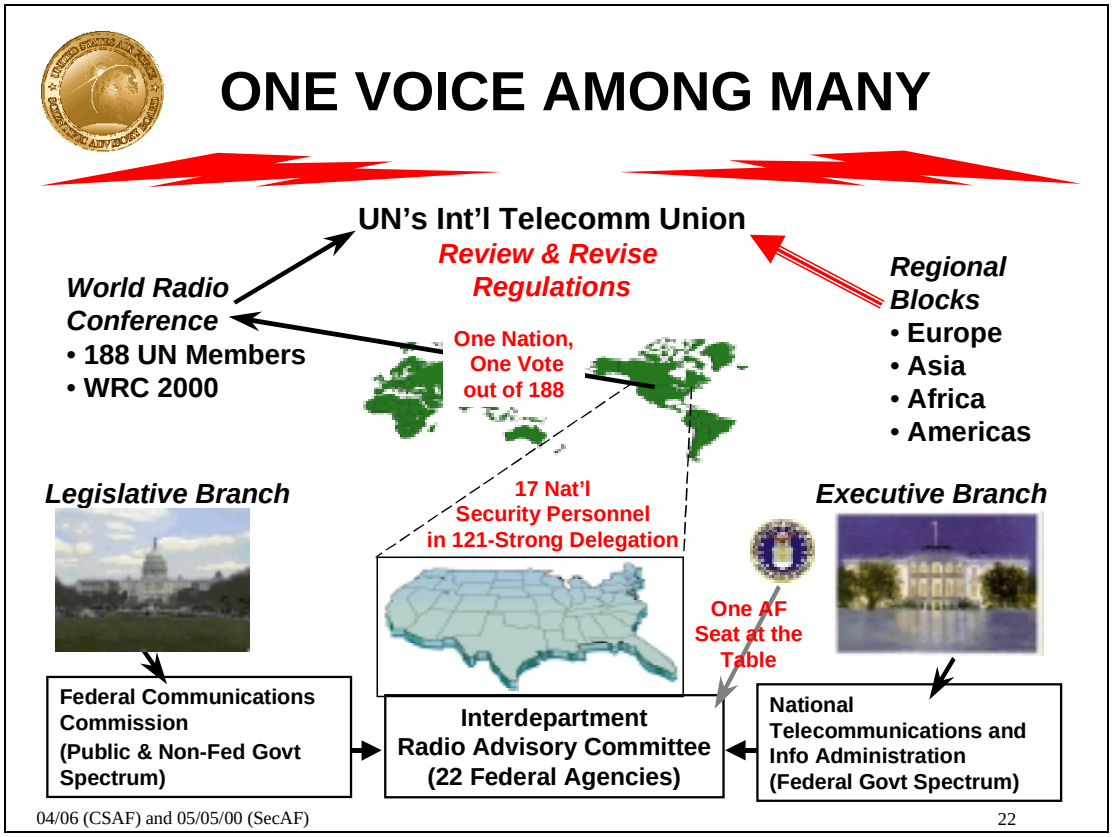
matters, leads the US delegation to the WRC. Industry has a heavy role through working groups and a central Advisory Group in advocating particular positions to the FCC. In addition, industry lobbies both Congress and the Executive Branch, and provides many advisors and support personnel to the US delegation. As industry becomes increasingly multinational, a given corporation may well work through more than one country's delegation to pursue an allocation decision motivated by its business interest. Finally, the US delegation goes to the WRC and negotiates with nearly 200 other countries, many of whom have very different agendas and each of whom has an equal vote in the outcome. The Study Panel was struck by two obvious aspects of this situation:

- Within the US, this is a political process with many players which relies on negotiation, coordination, and networks of personal contacts and relationships. Decision making is often protracted, issues are routinely tabled, and their resolution tends to emerge gradually from a consensus process. It can be frustrating to a military professional that there is no single civil entity to call or write to get a problem solved crisply and by a fixed date. AFFMA and the other Service spectrum management organizations have been very effective in supporting DoD interests in this environment, but they must do so within the constraints of the process.
- There is *no clear governance in the frequency allocation process that addresses national security concerns*. Furthermore, there is little awareness within the civil community of how spectrum decision, such as mandatory spectrum auctions, affect national security interests. While a commercial user can make a case based on economic benefit and be confident that the case will be understood by senior Administration and political leaders, a military advocate is handicapped both by the fact that many other participants lack military insight and the fact that tools to quantify and establish the military importance of spectrum are lacking. There is thus no way to ensure that national security will be properly balanced with other interests in allocation decisions, especially internationally. Combined with the limited level of effort DoD and the Services have devoted to this area, the result has been decisions both in Congress and in the ITU that have led to the spectrum losses cited



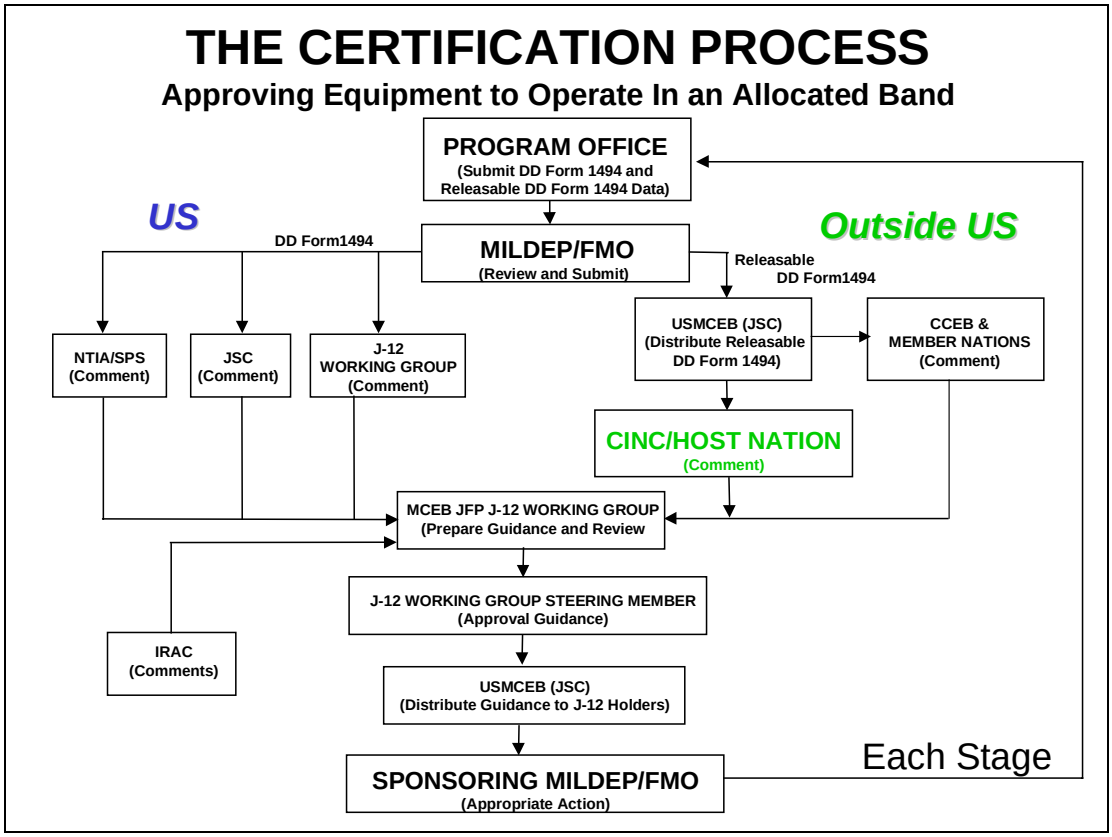
INTERAGENCY RADIO ADVISORY COMMITTEE (IRAC)

Chart 21 lists the IRAC membership. Note that agencies like the Postal Service, with minor interests in spectrum access, have nominally the same voice as the Services, FAA and NASA, although in practice the MILDEP members have a clear leadership role on Defense matters in this forum.



ONE VOICE AMONG MANY

One way to highlight the disadvantage of DoD in defending spectrum allocations is to show how the Services' voices are diluted in the process. This chart portrays the essential features of US participation in a WRC. Within the IRAC, DoD is represented by three of the 22 members, AF being represented by AFFMA. Although this is clearly a minority position, the fact that the MILDEP FMOs work together on national security spectrum issues at least ensures that these concerns will be voiced and strongly defended at the IRAC table. This is usually where the Services and DoD first become aware of how, at the national level, the many additional interests of commercial users through the FCC, as well as civil agency spectrum uses, may compete against military spectrum access. In the US delegation to a WRC, DoD has typically had one or two slots on a team of 160 or so personnel. Fortunately, reflecting much better US preparation for the upcoming WRC 2000, 17 of the 40 Government personnel in a 121 person US delegation are from the Services and Defense Agencies. Finally, at the WRC itself, the US gets one vote out of typically 188 participating countries. The situation might be likened to the United Nations without a Security Council veto. The point, once again, is that even vital DoD and AF spectrum needs are hard to defend in this structure. This is clearly one of the most important contributors to the spectrum challenge that AF and DoD face.



THE CERTIFICATION PROCESS

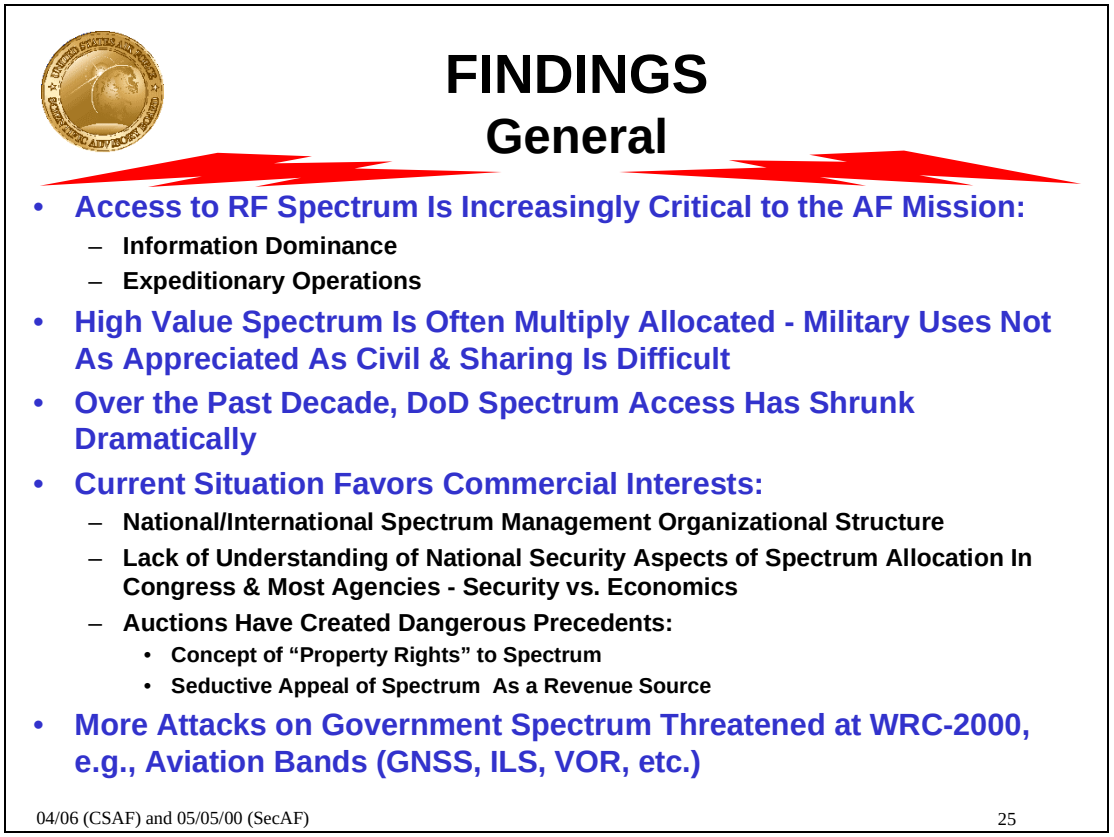
The final subject in this tutorial section of the report deals with the certification process. The chart is largely self explanatory, but several key points should be emphasized:

- The integrity of the process and a successful outcome depend on program offices preparing and keeping current their DD Form 1494 paperwork. SPOs must update 1494s as designs evolve, but in many cases there is little awareness of the importance of this process to the AF and no incentives or sanctions to promote compliance. Moreover, a SPO may go out of business or lose its developmental engineering capability once a system is fielded.
- Title 47 USC, OMB Circular A-11, DoDD5000.2R, AFD 33-1, AFI 33-118, NTIA Manual, and many other directives govern spectrum compliance. Compliance checks are mandatory at Milestones I, II and III.
- Early design decisions can have major unanticipated consequences later. *Spectrum issues should be addressed pre-Milestone 0!*
- The J-12 Working Group ultimately approves a certification recommendation that contains overall advice on how the SPO should address any spectrum-related issues.
- The process involves both US and overseas coordination. Host nation issues can take many months to work, can result in only temporary accreditation, and can be subsequently revoked. Accurate and current information generated by the J-12 process is crucial to timely and successful coordination of approval to use US and host nation spectrum.

Later sections of this report have more to say on needed improvements in the acquisition process to facilitate timely certification of new and modified systems and equipment.

SECTION 3: FINDINGS

In the following charts, the Study Panel presents its findings in the areas listed in Chart 24.



FINDINGS: GENERAL

This and the next chart capture as findings the underlying themes of the preceding discussion. The overarching finding of the study is that access to RF spectrum is already critical to the operational effectiveness of aerospace forces, is growing more so, and is acutely threatened. Even a vital service such as Link-16 operates as a secondary function under noninterference restrictions. The international spectrum process provides no guarantees of military spectrum access. As a result, historic spectrum allocations suitable for military functions have been severely curtailed, and the serious impacts to readiness, operational capability, and cost that have already occurred threaten to continue. DoD spectrum mangers routinely encounter the perception that DoD owns large amounts of spectrum and can afford to give up pieces of it. The truth is that DoD primary allocations represent less than 2% of frequencies below 300 GHz, and then only in the US. Since the 1970s, DoD functions have either lost the use of or been relegated to secondary status in bands totaling roughly 400 MHz, largely in the most valuable bands below 10 GHz.

Many factors contribute to the erosion of military spectrum access. Outside of a few specialized organizations such as AFFMA, there is a lack of spectrum awareness at all levels within the MILDEPs. Both much of the membership of the Congress and large parts of their staffs fail to appreciate the national security consequences of reallocations and, indeed, see the sale of federal spectrum as a quick source of revenue. At the same time, it should be noted that Congressional advocates of a strong national defense have pressed legislative initiatives to try to halt the slide. Other federal agencies, the FAA in particular, refuse to recognize defense as a priority equal to or greater than domestic demands for spectrum. Industry frequently sees major business opportunities threatened or stymied by lack of frequency allocations. One knowledgeable briefer described the recent trend in spectrum auctions as a "gold rush" in which enthusiasm has outrun rationality. Effectively, spectrum access has come to be viewed as equivalent to a property right, with the same legal standing and protections. This directly contravenes the more valid

view that spectrum is a limited resource like water to which permanent entitlement cannot be given. The generally unjustified assumption that spectrum sales will be major sources of Government revenue and the lack of a good way for NTIA and FCC to balance competing interests contribute to the problem. As a result of these auctions, the national security has suffered without the achievement of their proponents' claimed contribution to the nation's finances. The WRC 2000 agenda once again includes a number of issues that threaten spectrum access for vital military functions.

FINDINGS: GENERAL (Continued)

As earlier Sections have shown, spectrum management is both highly complex and profoundly politicized. Crisp mechanisms for analysis and issue resolution are lacking. Few senior decision makers in DoD thoroughly understand the situation or recognize its criticality. The AF and DoD are seriously handicapped in defending even their remaining frequency allocations, and reliance is placed on negotiation and consensus to ensure due consideration of national security needs, especially in the international arena. Fortunately, the FY 00 Defense Authorization and some other recent Congressional actions are encouraging; more detail is given below.

The fight to preserve spectrum access for AF and DoD is waged by a relative handful of largely unknown and unsung dedicated personnel. The ability to properly prepare for and participate in spectrum management activities, to give timely processing to paperwork, to anticipate and forestall problems, and to provide in-depth analysis and advice to spectrum users and system developers are all limited by available manpower and resources. Repeating an example cited earlier, spectrum managers at the MAJCOM and base levels are not, in general, placed at the appropriate managerial levels and do not have adequate operational analysis tools and databases to demonstrate and quantify the military value of spectrum and the economic consequences of reallocation.

The requirements definition process and the conceptual stages of an acquisition program must often deal, at least in broad terms, with spectrum issues. Even a conceptual description of a system will involve the general characteristics of sensors, communications, defensive systems, and so forth. The outcome of these activities may very well establish *de facto* spectrum access needs without adequate consideration of the long term implications. One way to deal with this would be to require a pre-Milestone O draft of a DD Form 1494 for an initial review by allocation and certification authorities to identify potential issues. This would then be refined for subsequent milestones as system details are settled. One final general

finding is that industry, especially DoD contractors, need more awareness of this problem and must take more responsibility for dealing with it. In a host of ways, from participation in WRCs to applying corporate resources to invent more efficient means of spectrum use, industry can and must partner with DoD to address this vital national security issue.

FINDINGS: OPERATIONAL/TRAINING IMPACTS

As the early part of this report has already discussed, loss of spectrum access threatens to impact every military mission, from humanitarian relief to major theater warfare. When spectrum is lost, the ensuing modification or replacement of systems and equipment can easily run to tens or hundreds of billions of dollars, as the NTIA 1998 report demonstrates. Moreover, DoD lacks a coherent, long term approach to the problem and is thus in the position of reacting to a succession of spectrum crises, especially in view of the organizational complexity and long time lines involved.

The situation can be expected to get worse. Warfighters will be increasingly constrained in the areas, times of day, transmitted power levels, and other parameters of testing and training. Even if such problems can be worked within the US, other nations, even nominal allies, have been increasingly unwilling to grant requested frequency assignments, sometimes ending a negotiation of many months with a denial. Some of these training deficits can be made up for in part through simulators. However, critical aspects of training and the ultimate assurance that our forces are ready to execute their missions demand a reasonable opportunity in all theaters of operation to exercise systems the way they will be employed. Our forces must be able to train as they fight, and today they are increasingly being denied that opportunity. The situation is especially serious overseas. Many frontline systems such as AWACS and JointSTARS interfere with commercial broadcasts and other civilian systems in Europe and elsewhere. Training with coalition partners, maintaining readiness of units stationed abroad, and conducting operations other than conventional warfare are among the activities hurt by the inability to use systems as they are designed to be used. Some ostensibly friendly nations use their sovereignty over spectrum as leverage in their relations with the US; at the least, this costs time and manpower dealing with issues that can seem to drag on forever.

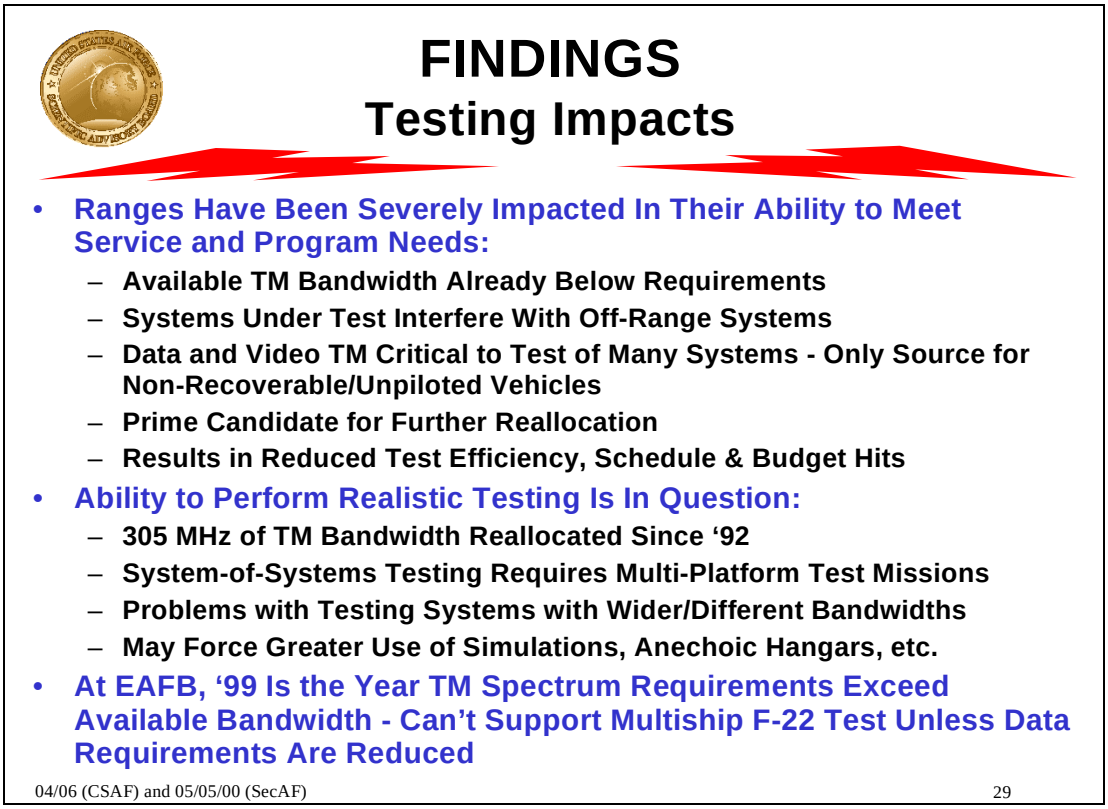
Advanced weapon systems, predicated in large part on exploiting information superiority, demand more spectrum for such functions as high resolution RF sensing, high capacity data link networks, and spread spectrum waveforms. Existing platforms will require spectrum-hungry modifications to maintain their effectiveness and survivability and will increasingly overlap with other critical national spectrum-dependent functions, such as air traffic control, national science activities, and services important to the economic base. Without adequate spectrum access, or in a situation where spectrum is only available in an actual contingency, such systems will be limited in the modes they can employ. The already thorny problem of securing overseas frequency assignments will only get worse as broadband/multiband systems come into the inventory. At a minimum, more innovative and flexible ways to share spectrum with civil and commercial users and to demonstrate noninterference will be needed.

FINDINGS: OPERATIONAL/TRAINING IMPACTS (Continued)

The Study Panel interviewed many frequency managers, and encountered a common theme that traditional options for coping with frequency requests are vanishing. In the past, organizations could trade frequency assignments for periods of time, coordinate operations to time share bands, and so forth. One of the reasons spectrum management has not been widely viewed as a serious problem is that the ingenuity and teamwork displayed by these managers have generally found some way to meet any given operational demand. As the "management reserve" of frequencies has shrunk to nearly zero, the ability to apply these workarounds is also going away, and operational frequency managers are increasingly frustrated as their support to their customers declines for reasons beyond their control.

In parallel with growing problems in day-to-day frequency management, senior spectrum policy managers are also running out of options. Even millimeter wave bands are already allocated or applied for by civil and commercial users; there is not much empty spectrum to move to, even if money were no obstacle. As noted earlier, both national and international frequency allocation organizations handicap DoD decision makers in establishing long range strategies, because any conceivable DoD spectrum usage plan runs counter to powerfully advocated non-defense uses. Virtually every feasible long term approach involves both introduction of advanced technology and modifications to or replacement of legacy equipment, and few such projects can be funded in the current budget climate. The fact that a commander can be penalized for even inadvertent interference with a commercial user was highlighted in the report introduction.

The need for better tools to quantify and defend the value of spectrum in national defense has already been mentioned. In the operational world, there are also shortfalls in the available tools both for supporting frequency management and deconfliction and for performing overall requirements analysis to ensure development and modification programs are spectrally feasible.



FINDINGS: TESTING IMPACTS

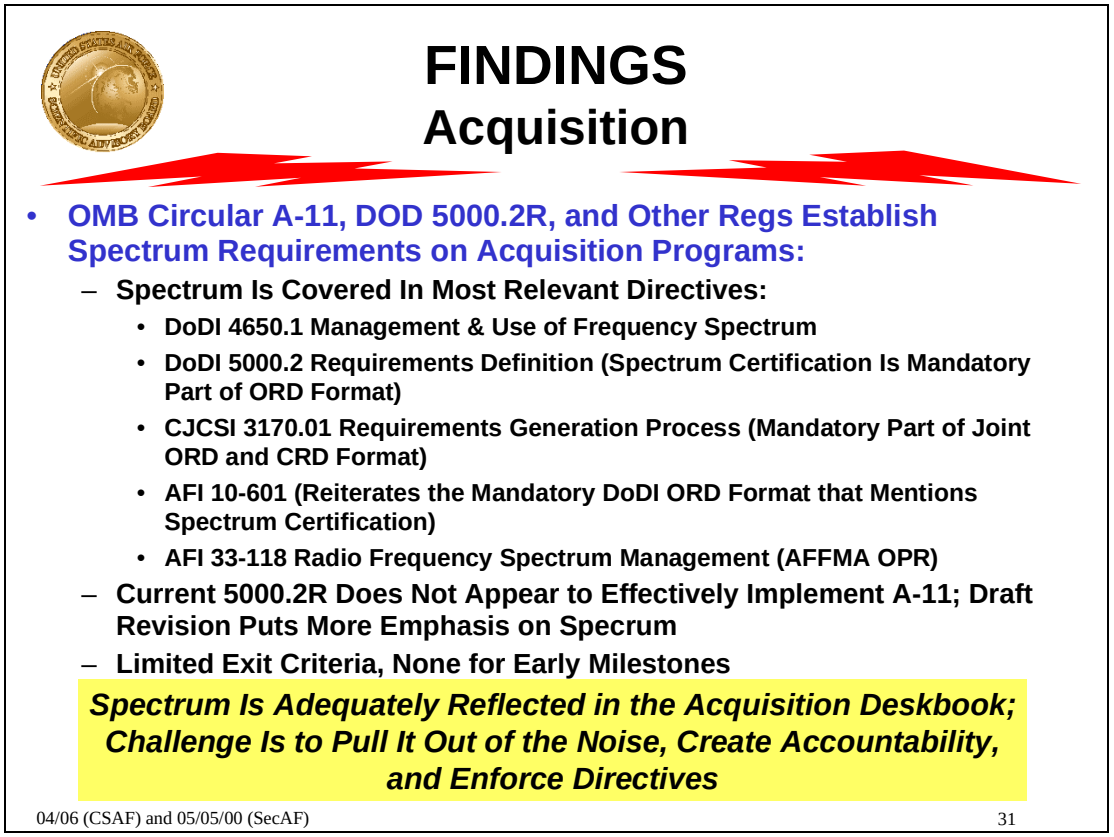
The loss of telemetry (TM) channels at Edwards AFB was one of the introductory examples of this report, including the stark reality that in 1999, for the first time, a major weapon system test may be unsupportable due to lack of TM capacity. All test ranges have suffered from the loss of channels and are threatened in their ability to meet customer requirements. In general, available capacity is already below the need, and further losses are threatened. This is especially crucial in testing missiles where onboard recording is not feasible and UAVs where instrumentation must compensate for lack of aircrew feedback. The overall problem of encroachment on test facilities by commercial developers, communities seeking to eliminate aircraft noise, and others is matched by problems with various electronic services adjacent to test ranges which may suffer interference from systems under test. Inescapably, loss of TM reduces test efficiency by requiring more missions to collect data, increases risk of failure to meet mission objectives, and adds to program schedule and costs.

Like every other aspect of the spectrum dilemma, problems with testing will only get worse. An example is the trend toward system-of-systems coordinated operation of aircraft and other systems. Realistic testing and training demand that missions involve representative numbers and types of platforms with realistic data links and other connectivity. Such missions are likely to demand more TM than single platform tests. Technical means such as bandwidth compression are feasible, but will entail the costs of replacing the existing inventory of TM assets. The other threatened impact on testing has already been mentioned – the ability to realistically test systems which use more and different frequency bands than older generations. As one example, the Joint Strike Fighter radar will have significantly greater bandwidth than the F-15/F-16 radars and will be able to operate in bands where other users such as government fixed, mobile and scientific services have priority. It may be necessary to limit some testing to anechoic hangers, but this will require a departure from a long-held belief that every mode of every system must ultimately be tested in the real operational environment to ensure proper performance and safety.

FINDINGS: SPECTRUM MANAGEMENT

Section 2 dealt in large part with issues specifically associated with the processes of spectrum management. The essence of the discussion can be captured succinctly in a finding with the following elements:

- The current system results from a law more than 60 years old and an essentially political process that is questionable in its ability to cope with a world of rapid change, disastrous spectral crowding, and growing reliance on spectrum for defense.
- If the needs of the nation and of the international community are to be met through the optimum use of the limited spectrum resource, some way to balance commercial and defense interests must be found. Today, virtually every issue is addressed through *ad hoc* problem solving, individual negotiation, personal networking, and similar methods because there is no adequate underlying structure for arriving at objectively optimum and timely decisions.
- The presence of Service representatives is seriously diluted at the IRAC, national and international levels, resulting in significant advantages to commercial participants. Moreover, Congress and the FCC tilt heavily toward commercial over national security concerns.
- The national process for preparing for and participating in the ITU is not as coherent, expert, and continuous as it needs to be, especially in dealing with other nations which build voting blocs, carefully prepare positions and support, and have experts with decades-long WRC experience.



FINDINGS: ACQUISITION

Many of the preceding findings concern things that are only partially if at all within the control of the AF. However, many important issues involve system requirements and acquisition, areas where the AF can and must act. This and the next few charts address some of these.

Spectrum requirements are established by public law and multiple implementing directives, (OMB A-11, DoD 5000.2R, AFD 33-1, AFI 33-118, *et al*). A review of the Air Force Acquisition Deskbook, done for us by AFFMA, indicates that spectrum is reasonably well covered as the directives listed in the chart show. Even so, the Study Panel has concerns that the current language of the master directive, DoDD 5000.2R, does not appear to be sufficiently specific and enforceable to implement Circular A-11; however, the draft of a new edition puts increased emphasis on spectrum. In particular, exit criteria for the various phases of the acquisition cycle do not include tough and concrete items in the area of spectrum, and the early milestones have none at all. This contributes to an overall situation in which, although various documents may contain appropriate language, spectrum is treated as one more issue among many, and the system does not apply the focus and accountability that are essential to enforce these directives and ensure spectrum is properly accounted for. The AF might reap great benefit from stiffening spectrum requirements in its own directives and paying greater attention to spectrum compliance in the AF Acquisition Board milestone process.

FINDINGS: ACQUISITION (Continued)

The reason early attention is important is that such early choices as the types of functions a system will incorporate and the bands where they will operate can have major subsequent implications. Prior to Milestone I, it might well be a matter of easy choice whether to predicate a system concept on high levels of bandwidth compression, use of still-available higher bands, use of EO vs. RF for a given function, and so on. Yet good decisions here might avoid spectrum conflicts and serious budget and schedule impacts years later. Also, checking spectrum access during the developmental and operational testing prior to system deployment would provide a feedback mechanism for project personnel and establish a further link between the spectrum and acquisition processes.

A host of reasons prompt the Panel to urge earlier attention to spectrum issues. Efficient and affordable methods for spectrum use may be identified at a point in concept definition where there is little or not impact from adopting them. The long lead times of these processes, which are almost entirely beyond the control of the AF, dictate that AFFMA and other responsible frequency management organizations be given maximum time to work issues. Moreover, long term projection of spectrum needs is essential to DoD planning and policy formulation. Commercial spectrum users routinely file for spectrum allocations well in advance of developing or deploying actual systems. Already, AFFMA is being forced to defend AF access to millimeter wave bands where little or not activity currently exists. Overall, early attention to spectrum issues enables AF to support its own and DoD allocations and to make the best use of available spectrum.

Recent experience has shown that the increasing emphasis within DoD on use of commercial off the shelf (COTS) products has spectrum implications that may not be recognized by the organizations deciding on such purchases. Systems such as wireless local area networks, which are approved for use in the US,

have been prohibited overseas, to the discomfiture of units which planned to use them as an inexpensive means of setting up data communications at deployed locations.

The Study Panel met with organizations responsible for classified programs to address the implications of these on the spectrum problem. Obtaining and protecting spectrum access for highly classified programs is obviously a significant complicating factor, and one which in earlier times was often ignored. Progress has been made in recent years, and the Panel found that, in general, the same measures needed for overall improved Defense spectrum management would address the needs of classified programs. However, continued attention and further steps are required, especially to find ways to ensure spectrum access and compliance for classified programs within the allocation and certification processes while preserving security. This is not a matter that the classified system community can (or wants to) ignore.

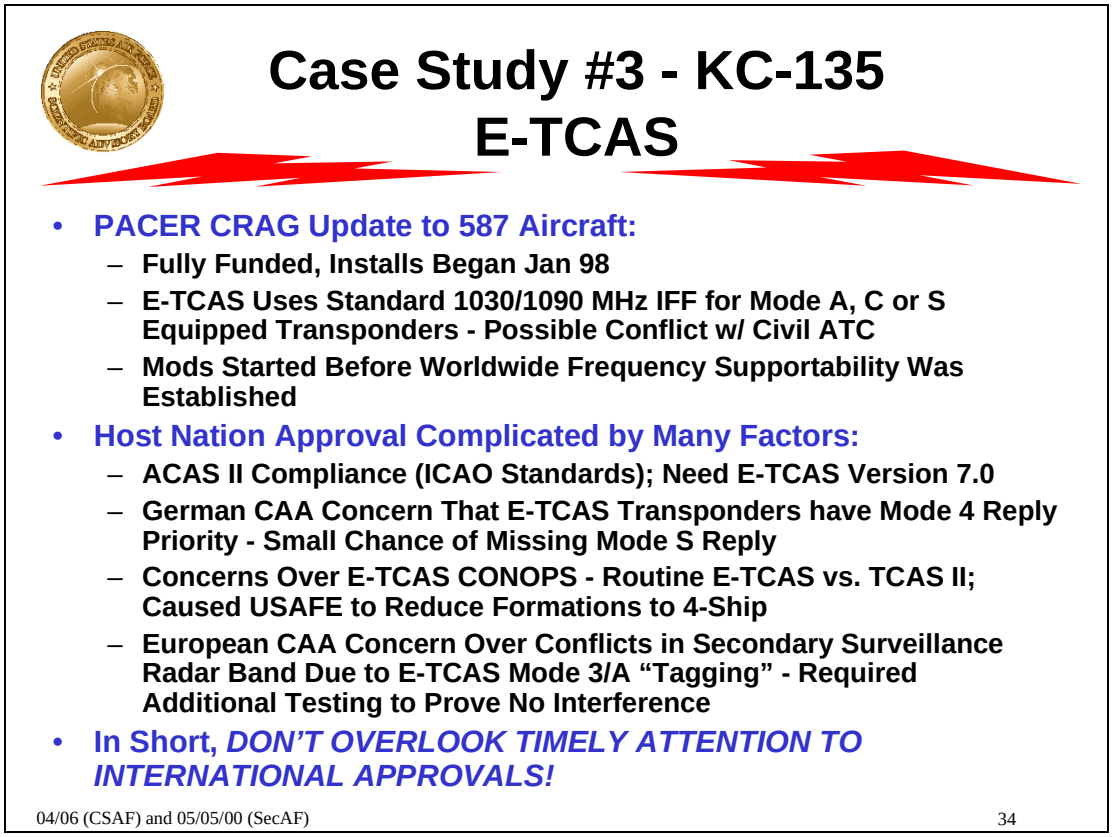
FINDINGS: ACQUISITION (Continued)

The traditional independence of each program office to pursue the most cost effective solution to program requirements acts to the detriment of coordinated planning for spectrum use. The Study Panel expects that there will be increasing instances where compatibility with legacy and planned systems, tradeoffs among systems for use of particular bands, and other such factors will require overall spectrum decisions that transcend individual programs. As an example, even the 94 GHz millimeter wave band already has multiple contending proposed uses, including commercial systems. A DoD position on allocating this spectrum is essential both to defense of military allocations and to deconfliction of the band among military systems.

At the same time, the personnel, tools, procedures and other infrastructure elements that are essential to good spectrum management at all levels of the acquisition community need significant strengthening, especially at Acquisition Centers and program offices. This finding applies equally to Government organizations and to their contractors. Historically, frequency management has been a communications function, reflecting the legacy of operational frequency management, and with support to acquisition treated as a sideline, if not an afterthought. The Study Panel found that Space and Missile Systems Center (SMC), among the AF acquisition centers, has done the best job of giving the Frequency Management Office (FMO) the visibility, access, and resources to support SMC SPOs and programs. Even so, a case can be made that additional resources are justified. At the other Centers, the FMO tends to be a low level function within the base communications squadron. SPOs often fail to appreciate the importance of working spectrum issues, involving Center and Command FMOs early, availing themselves of available expertise, and keeping spectrum paperwork, especially 1494s, current. There is a shortage of acquisition engineers with spectrum management credentials and experience, and SPO personnel often lack the skills to tackle these matters. The lack of tools and data bases mentioned earlier

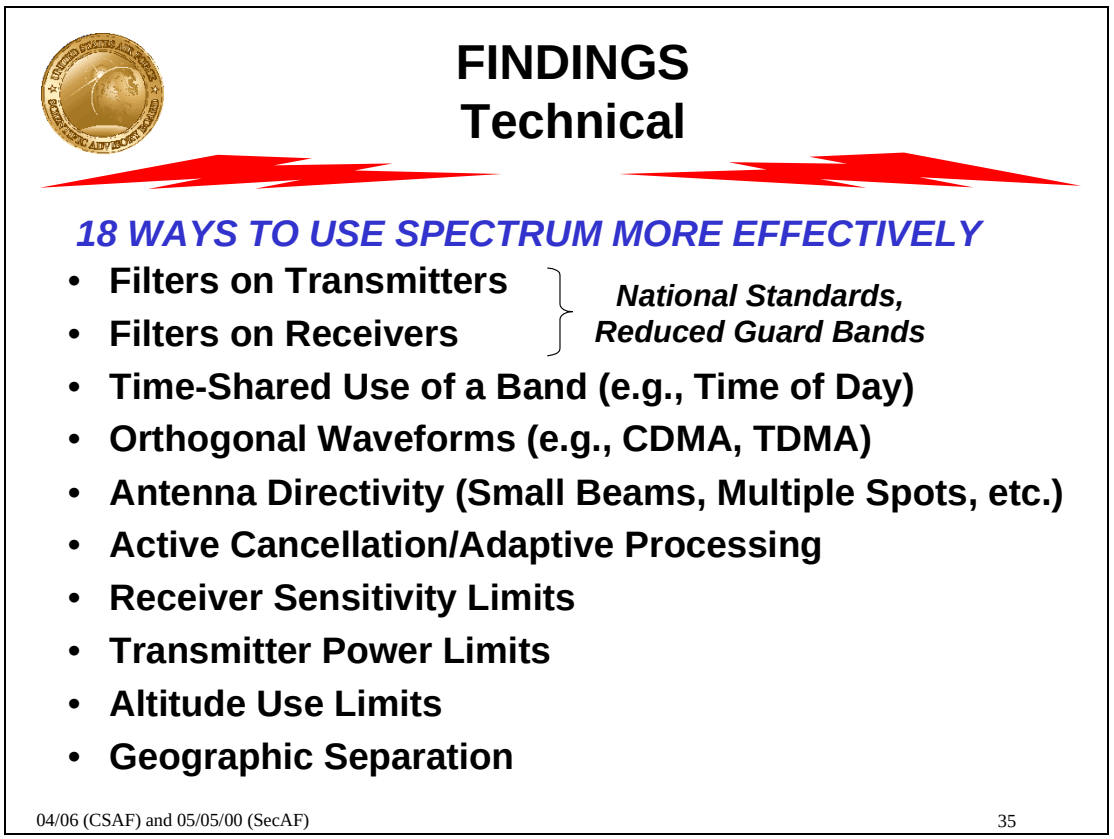
shows its effect here as well, because such support might make it less painful for SPOs to give spectrum the attention it deserves.

In short, acquisition organizations frequently lack both the incentive and the means to address spectrum in a timely and effective way. The AF pays a heavy price for this neglect in dealing with the multitude of problems that result in system development, test and operation.



Case Study #3: KC-135 E-TCAS

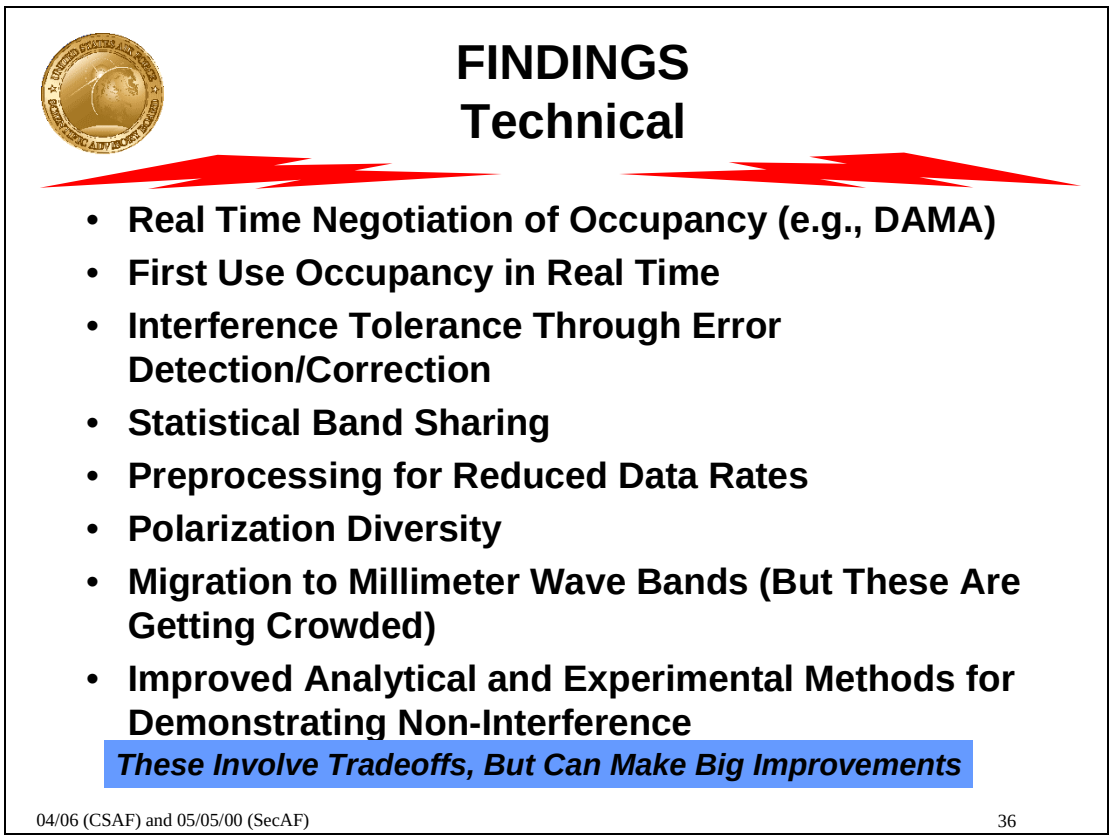
The installation of the Enhanced Traffic Alert/Collision Avoidance System (E-TCAS) provides an example of the pitfalls of spectrum in the acquisition business. As part of the PACER CRAG avionics upgrade to the KC-135 fleet, E-TCAS is an important element of keeping these vital aircraft mission capable and compatible with civilian air traffic in the decades ahead. However, the program failed to address the international compatibility of the system and proceeded with installations before spectrum coordination was complete. The initial fielded configuration was not compliant with International Civil Aviation Organization (ICAO) standards. The technical details are complex, but various European countries and agencies expressed concerns over real or potential conflicts between E-TCAS and civil air traffic control systems. The result was a major effort in additional system development and testing and in difficult international coordination before tankers in Europe could use E-TCAS. Even so, the originally planned size of tanker/receiver formations had to be reduced. Much or all of this could have been avoided by timely attention to spectrum approval. As this report was being finalized, the Panel learned that Germany has issued a limited (three-ship formations) approval for Version 6 of the E-TCAS software.



FINDINGS: TECHNICAL

The Study Panel combined the first hand knowledge of the members and information gathered during the study to compile a list of ways to get more functionality out of a given bandwidth. A representative measure of effectiveness is spectral efficiency, defined as the number of bits per second of actual information that can be transmitted per Hz of bandwidth. Typical communications systems today manage between ½ and 1 bit per Hz. Even a doubling of that figure would go far to coping with limited spectrum access. Various ways to compress information so a given bit stream needs less bandwidth, to reuse frequencies by allowing separate simultaneous transmissions, to multiply effective channels by allowing some users to transmit when others are idle, and similar basic ideas have real potential here.

This and the next chart list 18 such schemes. More details are given in Annex C. For the present, the message is that the means exist to do much better than current systems and that this is a critical element in any formula for mitigating the impacts of loss of spectrum for defense systems.

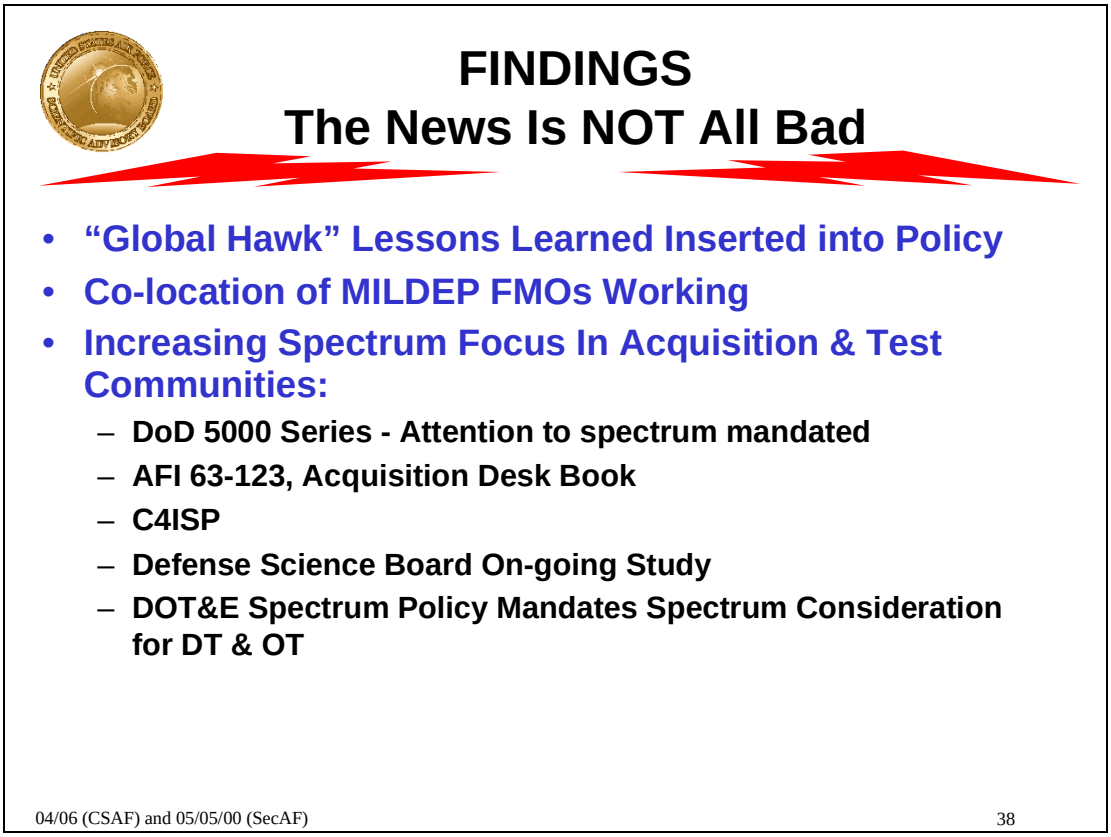


FINDINGS: TECHNICAL (Continued)

The rest of the list. Note that use of these techniques will inevitably involve tradeoffs among various technical and cost factors in system engineering and design.

FINDINGS: The News Is NOT All Bad

Before leaving the Findings section, the Study Panel wants to emphasize that recent happenings provide grounds for optimism that at least some defense spectrum issues are beginning to be understood and addressed. The best news comes with the FY 00 Defense Authorization which puts Congress on record as recognizing the impact of spectrum reallocation on military preparedness, reverses part of the most recent reallocation, and calls for a badly needed interagency review of way spectrum is planned and allocated in this country. This bill indicates Congress is beginning to realize that it must help protect DoD's access to spectrum and creates valuable momentum which DoD and AF may be able to exploit. Several other actions, some individually small, but collectively significant, are listed in the chart. SECAF and other senior officials, including ASD/C3I, JCS/J6, Director DISA, AF/SC and others, have used Congressional hearings to raise spectrum concerns and heighten awareness of the potential impacts of any further spectrum reallocations. Within DoD, an overall "Spectrum CONOPS" to better coordinate analysis, planning and decisions is being worked, and regular reports are now required to DEPSECDEF. The relatively recent concept of a system C4I Support Plan is catching on (a prominent example is that for the Joint Strike Fighter) and promises to help surface and resolve spectrum issues. Air Combat Command and Electronic Systems Center have placed renewed emphasis on tracking spectrum matters. In a hopeful sign for joint spectrum management, AFFMA was recently invited to help the Army with course material. At least some spectrum managers have been given enhanced authority and visibility to do their jobs more effectively. In short, while daunting problems remain, a useful start has been made on recognizing spectrum concerns and dealing with many of them.



FINDINGS: The News Is NOT All Bad (continued)

The recent loss of a Global Hawk due to an inadvertent transmission from a ground facility on the command link of the flight vehicle has been taken to heart and reflected in policy. The decision several years ago to collocate the Frequency Management Offices of the Services, plus the Office of Spectrum Analysis and Management, in a common office suite has been even more successful and productive than hoped. This situation allows much closer coordination, allows the key DoD spectrum management staff to be mutually supportive, and helps immensely to ensure that DoD speaks with one, well supported voice in the IRAC and other fora. The chart lists a number of areas where spectrum is, or soon will be, better represented in policy, directives, and procedures of the acquisition and test communities. There is positive momentum here which must be exploited and continued.

SECTION 4: RECOMMENDATIONS

The next seven charts present specific recommendations, some of which can be directly implemented by the AF and some of which require the AF to work within the larger DoD community to pursue needed changes.

RECOMMENDATIONS: CONTINUE TO RAISE AWARENESS OF SPECTRUM ISSUES ACROSS THE AIR FORCE

The spectrum access crisis has crept up on the AF over the course of several decades. Dealing with it will require management attention and prolonged, coordinated action. The Study Panel believes that an important early step is to get spectrum on the leadership "radar scope" through a structure that ensures the situation is periodically reviewed so that timely and effective measures can be taken to deal with spectrum issues. This could be accomplished in a number of ways, building on the initiatives discussed in the Findings section of this report. As an example, the Panel suggests periodic briefings, at least annually, to the AF Board of Directors by HQ AUSAF/SC, which has responsibility for spectrum management for the Department of the Air Force. Spectrum issues are part of the regular weekly SC and AQ Chief Information Officer (CIO) meetings; these discussions would be enhanced by periodically including a spectrum POC from the XO staff to ensure operational community awareness and involvement. To promote awareness and proactive measures to either head off spectrum problems or minimize their impact, the annual report should be built around a forecast of likely issues and their potential impacts. For example, a number of proposals that threaten reallocation of spectrum important to the AF are expected to appear on the agenda of the next WRC. Another theme of this review would be a status report on compliance with spectrum policies and directives in acquisition programs and in AF unit operations. The Panel believes this approach would both surface spectrum concerns to senior leadership and provide a foundation for working with the IRAC, with OSD spectrum officials, with the other Services, and with other agencies to defend DoD and AF spectrum access and make most efficient use of the spectrum that is still available.

An important dimension of this overall awareness-raising is visibility and access to leadership on the part of AF spectrum managers, especially in the Acquisition, Logistics and Test Centers. This critical activity

belongs on the Center Commander's staff, as has been done at Space and Missile Systems Center, not in the lower echelons of the base communications squadron. The Center Frequency Management Office (CFMO) should be positioned, staffed and empowered both to provide necessary support to individual programs and to serve as a key source of information and warning of potential problems up the acquisition command chain. This would be a major input to the annual spectrum review and would help ensure that program offices pay proper attention to spectrum questions.

The Panel wishes to stress that this proposed review must not degenerate into just another paper drill on top of the reporting requirements that spectrum management staffs must cope with already. The idea is to focus on spectrum in a forum that gets issues in front of the right decision makers and facilitates timely actions. In the past, AF leaders have often had to deal with spectrum in the form of crises demanding urgent response, responding to situations that might have been prevented or mitigated by early action. The annual review, or some other appropriate mechanism, is intended to replace this reactive mode with one that coordinates the full range of AF actions affecting spectrum to support spectrum management organizations, develop long range spectrum planning and strategy, make good acquisition and operational decisions, and keep crises from occurring.

RECOMMENDATIONS: GROW SPECTRUM COMPETENCE

All the advance planning and analysis in the world will do little good if the means to carry out effective spectrum management are lacking. The Study Panels recommends a number of steps to increase spectrum competence across the activities described earlier in this report. Specifically:

- Program office personnel, both managers and engineers, need a basic understanding of spectrum just as they do of safety, testability, maintainability, and many other factors to be balanced in system designs. This is not to argue that every SPO engineer or program manager must be a spectrum expert. It is to argue that these key decision makers need the ability to properly evaluate spectrum concerns against others and to recognize when a problem arises that warrants bringing in dedicated spectrum management capability. One obvious step is to cover spectrum in the education of SPO personnel. The Panel realizes that many important topics compete for space on crowded curricula at schools like the Defense Systems Management College (DSMC) and the Air Force Institute of Technology (AFIT). At least one DSMC elective course covers spectrum now. The Panel believes this should be a mandatory topic on the way to certification as an Acquisition Professional.
- A smaller number of acquisition professionals need the in-depth expertise to work spectrum analyses and design trades. The Panel believes that technical means exist to use limited bandwidth for much greater functionality, as noted in a Finding. Exploiting these, however, demands the necessary expertise in both program office and contractor technical staffs. Major programs with large spectrum involvement could well merit qualified spectrum analysis and management experts on a full- or large fraction of full-time basis. A larger number of engineers who work on sensors, radios and other RF systems, while not dedicated to spectrum analysis, should have the necessary education and hands-on experience to work routine spectrum questions

and assist outside experts in grappling with individual problems. Possession of this expertise should be career enhancing; both military and civil service personnel systems should have the ability to track this, like other, specialized capability and should promote career progression that broadens expertise and accounts for it in promotions. Taken together with the recommendation to elevate CFMOs to the appropriate level of visibility and authority, this increase in expertise will go far to ensure that spectrum is properly dealt with in acquisition and support programs.

- On the operational and policy sides of the spectrum community, the Panel believes that current staffing levels are insufficient for the combination of working current issues and conducting long range analysis and planning that the spectrum situation demands. The heavy OPTEMPO burden on operational frequency managers and the fact that organizations like AFFMA have all they can do to put out fires that are already raging have been noted. The Panel recommends an analysis of current and projected workload, staffing levels, and other relevant factors to determine the appropriate increase in numbers, which the Panel expects to be quite modest in view of the seriousness of the situation. This is the one recommendation coming out of this study that involves adding resources; the Panel believes the long term cost avoidance from prevention of future spectrum problems will more than repay the expenditure. As with the acquisition field, spectrum expertise in these areas must be identified, developed, valued and provided with effective career field management. This applies to officers, enlisted personnel, and civilians.

RECOMMENDATION: MAKE SPECTRUM MANAGEMENT A CENTRAL PART OF ACQUISITION

The preceding recommendation included the need for more personnel with spectrum expertise in program offices. This one deals with detailed aspects of improved spectrum management in the acquisition *process*. This is a complex subject with a number of important aspects.

As with every other dimension of a system development, a successful outcome must begin with good requirements. While avoiding the common sin of over-specifying system characteristics, a good requirements document should nevertheless incorporate the realities of limited spectrum availability just as it does those of performance levels, cost and compatibility with expeditionary operations. This encompasses such things as types and performance levels of sensors, connectivity among platforms, interoperability, and levels of on-board processing and system autonomy. It would be very helpful if spectrum availability were incorporated as a basic consideration in Analysis of Alternatives and other up-front activities leading to the structuring of a program.

Within the AF milestone review process, if not the Defense Acquisition Board (DAB), the Panel advocates making spectrum availability a mandatory subject at *every* milestone, starting with Milestone 0, for any system whose operation requires use of the EM spectrum. The reason is simply so that this vital dimension cannot be ignored or treated as an afterthought. Even at the conceptual stage of system evolution, a first DD Form 1494 can be accomplished as the foundation for the successively more detailed versions that will emerge as the program progresses. Among other things, this will help promote proper attention to choice of bands, use of spectrum-efficient designs, and early attention of potential allocation and certification issues. The spectrum concerns identified in the Finding on testing should be addressed from the first draft of the Test and Evaluation Master Plan (TEMP). Finally, the process should emphasize the timely preparation of successive versions of the 1494 to keep current with the evolving

design and provide the necessary ammunition for CFMOs and AFFMA to work any allocation, Certification and frequency assignment concerns.

The Study Panel found that even when competent spectrum support is available from CFMOs and AFFMA, program offices often fail to avail themselves of it. A combination of properly positioning CFMOs in the organizational structure and of oversight emphasis on the appropriate interactions could minimize this unnecessary source of program risk. Similarly, program managers should be in no doubt that compliance with applicable law, policy, and directives on spectrum is a real factor in their success and evaluation; many will find this countercultural since spectrum has generally not been regarded as important in the past.

Many areas of spectrum management would be improved by better tools and databases. Acquisition is clearly one of these; program offices need easy access to information and decision aids to support design trades and other decisions involving spectrum. The Panel believes a number of computer programs that would do much of this job exist in various forms and places and that it would not take much time or expense to roll out the required capability.

Systems are built by contractors, and better spectrum management in acquisition must ultimately play out in acquisition strategies, contractor selections, and contracts themselves. The Study Panel believes that contractors can and must be enlisted as partners in developing and supporting systems that deal effectively with limited spectrum access, as well as in the larger sphere of helping DoD and the Services defend spectrum allocations. Spectrum access is a Government responsibility, but contractors can be tasked to support the analyses, data packages, and other activities that support allocation and certification. Going further, efficient use of spectrum is a legitimate performance requirement. Contractors can be incentivized to seek innovative ways of dealing with spectrum problems through Statement of Objectives (SOO) paragraphs and Instructions to Offerors (ITO) dealing with spectrum management approaches. The role of the contractor in achieving certification should be spelled out contractually in each acquisition phase.

The typically long lead times associated with allocation and certification decisions create special problems in today's world of information-intensive systems and rapidly changing technology. The evolutionary spiral has emerged as the best approach to refining requirements and evolving effective designs for such systems. At Electronic Systems Center (ESC), the standard for completing an iteration of the spiral is 18 months. The only way this necessarily rapid pace can be harmonized with the time scale of spectrum decisions, especially internationally, is to start early, including an initial 1494, and then run a parallel spectrum management process that tracks the evolving design and incrementally modifies the spectrum position as necessary. The revision to AFI 63-123 now in coordination should address this. In this situation, diligence on the part of the program office in keeping the 1494 current is especially important.

Ultimately, both program offices and their contractors must be accountable for doing everything required to work spectrum issues. It is not acceptable for program offices to assume that AFFMA or other exogenous organizations have the responsibility alone to solve these problems.

RECOMMENDATION: PUSH POLICY CHANGES TO BASE INTERFERENCE ASSESSMENTS ON *ACCEPTABLE* ENGINEERING PRACTICES

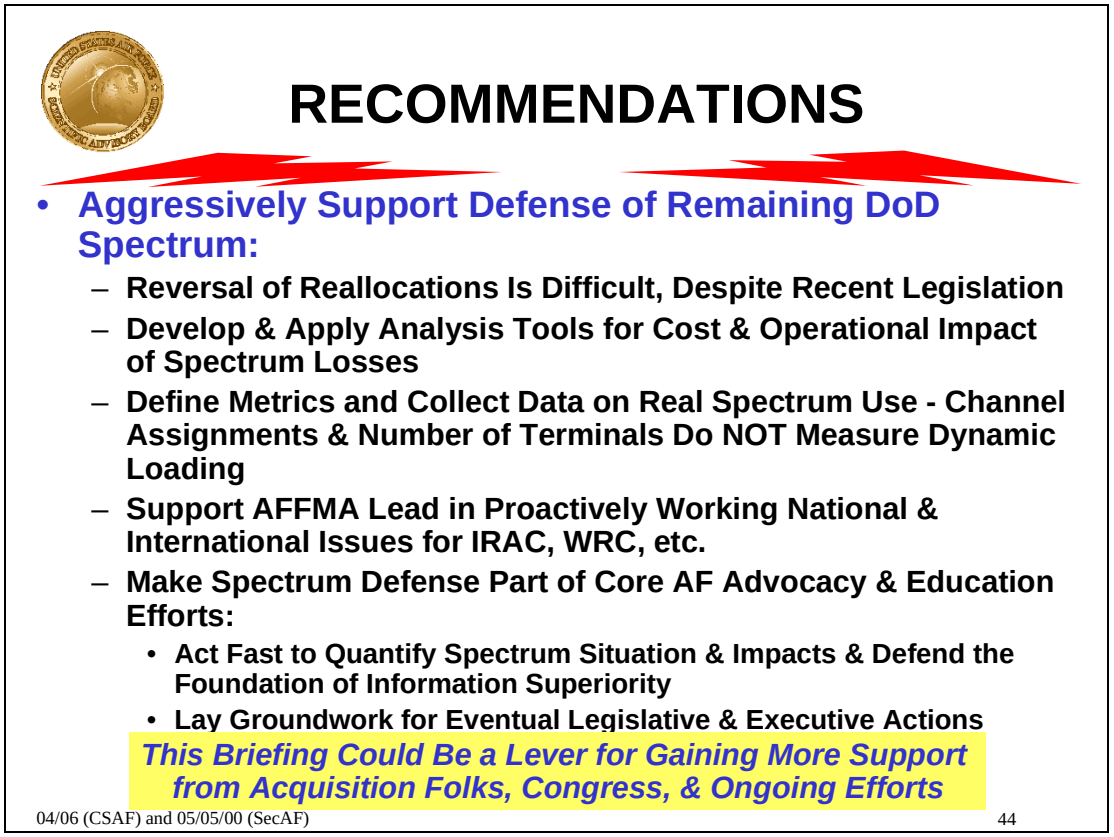
There is no obvious way to deal with spectrum crowding that does not involve better sharing of frequencies on the basis of mutual noninterference. Problems like the inability to share spectrum with air traffic control systems have arisen when contending users are unwilling or unable to do the rigorous engineering analysis and testing necessary to establish true interference thresholds. Without minimizing the difficulty of these calculations and tests, the Study Panel believes strongly that all the requisite means to perform accurate and robust interference assessments exist and are well understood. The propagation of EM waves and the ways complex mixes of signals affect and are processed by receivers can be modeled to very high levels of fidelity. Measurement techniques for electromagnetic interference and compatibility (EMI/EMC) are mature and widely practiced. What is needed is a national policy that assessments of whether one system interferes with another be based on such valid engineering practices, not on arbitrary rules of thumb or so-called safety factors that have no basis in reality.

Ultimately, this could well be part of a drive toward national standards covering things like selectivity of commercial receiving equipment, that is, the extent to which such receivers reject signals at frequencies outside their nominal operating range. The GAO report cited in the first section of this report noted that the absence of such standards contributes to the overall spectrum problem. Nationally accepted thresholds below which interference does not occur would be especially important in widely proliferated items such as portable terminals where the potential for conflicts is widespread.

A rational policy on spectrum sharing should also address the power of technologies such as digital radio, which can recover signals in the presence of much higher levels of noise and interference than older analog equipment. Applying the same interference criteria to such new designs as to older models is absurd, but no policy or standards currently recognize this. Another emerging area is that of ultra-

wideband signals which have very low power levels at any given frequency, relying on compressive receivers or other techniques to reconstruct a signal. Such a transmitter may very well radiate tiny amounts of power in many bands allocated to other users, but at such low levels as to cause no effective interference. A simple minded rule that the only acceptable signal level from a potential interferer is zero makes the use of such devices difficult or impossible while contributing nothing to the satisfactory operation of the equipment allegedly interfered with.

The standard of interference should be whether one system degrades the ability of another to provide its intended service to its users. Reasonable safety margins are in order, especially for critical functions like radionavigation aids that impact safety of flight. The Panel recommends that the AF take the lead within DoD, perhaps through the Joint Requirements Oversight Council (JROC), to formulate an effective national policy and advocate it up the administration, to the White House if necessary. The fundamentally political nature of the spectrum management process, dwelt on in detail earlier in this report, means that a simple "command decision" is likely to be hard to obtain. High level contact between DoD and the FAA may well be in order, with the White House as the ultimate decision source. There is abundant evidence in reports like those cited, in years of work in many laboratories on EM effects, and in practical field experience to support the recommended approach. The Panel understands that this will be a long and arduous proposition, but the urgency and potential benefits of obtaining a rational spectrum sharing policy warrant the effort.



RECOMMENDATION: AGGRESSIVELY SUPPORT DEFENSE OF REMAINING DOD SPECTRUM

Although it is highly encouraging that the latest Defense Authorization gives back part of the spectrum reallocated to the civil sector, suggesting that decisions detrimental to national security can be reversed, history suggests that attempts to reallocate defense spectrum will occur again. It is therefore imperative that AF and the other Services do everything possible to support concerted DoD action to preserve what remains of allocations important to defense users. One of the greatest needs identified in the course of this study is for better tools to establish and quantify the military value of spectrum, as noted in our Findings. Such tools would be a natural extension of those used in joint operational analysis and training. Products could include data on the outcome of operational scenarios under various situations of constrained spectrum access, on the costs and readiness impacts of training work-arounds, and on the costs to modify or replace equipment.

One problem in defending spectrum is that there is actually very little credible data on how heavily existing bands are used. Simply counting terminals, assigned channels or users fails to account for the inherently "bursty" nature of most message traffic. The Panel strongly suspects that much "scarce" spectrum is underutilized; at the very least, data will be essential to make the case against prospective commercial users that the military has too little spectrum to give any more up. As a side benefit, such data would materially assist operational frequency managers in making assignment decisions. It is quite feasible to instrument major exercises, perhaps even actual operations, with spectrum surveillance equipment and to record operations of terminals and other spectrum-using systems. Exhaustive data collection would be prohibitively expensive, but the Panel believes that a very useful factual basis for spectrum defense can be compiled at little cost or impact to operations. In addition, a soon-to-be-completed warfighter spectrum requirements study offers factual data to build a credible defense of DoD

spectrum access requirements. Advocacy should build on recent Congressional language supporting DoD spectrum needs.

The AF leadership should make support to AFFMA, the DoD Director of Spectrum Management, the IRAC, the Working Groups which help prepare for a WRC, and others involved in spectrum management a priority. As this report has stressed repeatedly, there is a great need to transform AF spectrum management from a succession of crisis reactions to a position of proactively working the system. AF/SC has successfully included spectrum issues in, e.g., SECAF's confirmation hearings. It is important to continue to put spectrum routinely on the agenda for AF senior leadership interactions with Congress, industry, and other organizations to which the AF advocates its positions on important matters. Assuming that changes in national policy and even legislation will ultimately be necessary to resolve the spectrum access crisis, such contacts could begin to lay the foundation. In addition to the specific spectrum personnel actions advocated in an earlier recommendation, AF should consider making spectrum a topic in officer education programs in general.

In short, the AF should seek and exploit every opportunity to make the case for the importance to national defense of preserving spectrum access. The Panel offers the suggestion that this report, possibly expanded, could be one tool for this advocacy campaign.

RECOMMENDATION: IMPROVE THE FREQUENCY MANAGEMENT PROCESS

Section 2 of this report describes the very complicated, politically oriented organization and process through which the nation addresses spectrum management. It would be in the national interest if this accretion of consensus were to evolve into a forum; that more efficiently and deterministically weighed spectrum allocation alternatives and balanced competing interests. The Study Panel recommends that the AF begin to work on this agenda, which will of necessity be a very long term proposition, on two fronts. Within DoD, the good start made by the 1998 DoD IG report should be continued and built upon to continue cleaning up the roles, responsibilities, relationships and procedures of the many organizations involved spectrum management. If DoD cannot unilaterally reform the larger spectrum situation, it can at least get its own house in order. The Panel was told that an initiative is underway within OASD/C3I to arrive at just such a clarification, a sort of "CONOPS" for military spectrum management. The AF encouraged this activity and participated; support should continue.

As one way to start the debate on the national process, the Panel recommends that the AF sponsor an independent, intergovernmental study of that process, perhaps under the aegis of the National Academy of Engineering or some other respected and authoritative body. Typically, such efforts consume several years, but the result could well go far to surface the problem, explore the alternative futures, and begin to build a political consensus for reform. It's worth a try. The language of the FY 00 Defense Authorization may provide the required basis to launch this study as part of a Government-wide review of national spectrum management.

RECOMMENDATION: WORK WITH RESPONSIBLE MEMBERS OF INDUSTRY TO ADVANCE NATIONAL SECURITY SPECTRUM ACCESS

An earlier Recommendation on acquisition stressed the importance of partnering with industry to work spectrum problems. This Recommendation expands on the desired relationship in several respects. First, it is important to distinguish between firms which act responsibly with respect to national defense concerns and those which seek only commercial advantage. In general, defense contractors, including those with significant commercial business that depends on spectrum access, fall into the former category, although there will, inevitably, be issues involving companies that seek aggressively to enter civilian telecommunications markets. Indeed, the Study Panel believes such companies can offer valuable insights and innovative approaches in balancing defense and non-defense uses of spectrum precisely because they have business goals in both categories. At the same time, it's clear that companies who see current allocations as a bar to their business and who have no involvement in defense have pushed and continue to push the kinds of reallocations that have contributed to the current access problem. DoD and AF need to interact with industry to deal with the problem but must do so in full knowledge of the interests and behavior of any given company.

Companies that do have the security of the nation as a core value can help in a variety of ways. One is to facilitate better use of commercial systems and services so that DoD gets maximum utility out of spectrum not allocated to military functions. Another is to cooperate in dealing with Congress and other agencies where private industry has access and clout not available to DoD personnel. Similarly, the central role of industry in preparing for and participating in WRCs and other spectrum events creates the opportunity for cooperation to pursue security objectives. From developing better technical means and system designs for efficient spectrum use to advocating defense interests in the political arena, industry can be a powerful ally and should be cultivated.

This report noted earlier the desirability of national standards that would reduce the susceptibility of commercial equipment to interference and, conversely, the chance of such equipment being an interference source. DoD has a long history of productive involvement in national standards bodies such as the Society of Automotive Engineers (SAE) and Institute of Electrical and Electronics Engineers (IEEE). Other industry bodies such as the National Defense Industry Association (NDIA) and Armed Forces Communications/Electronics Association (AFCEA) are also in a position to influence both the overall national policy on spectrum use and the directions industry takes in areas like standards. The Panel urges the AF to pursue through its members on appropriate panels and committees the support of such organizations for development of the needed commercial standards.

SECTION 5: SUMMARY

To recap, the AF and DoD confront an existing and worsening lack of access to spectrum, balanced by recent events which suggest that many aspects of the problem are recognized and being addressed. The entire defense community is affected, and the degradation of training, testing and even operations threatens mission accomplishment across the range of contingencies and levels of conflict. The AF and the other MILDEPs participate in and can strongly influence, but have little direct control over, the national and international organizations and processes through which allocation, certification and assignments are worked. These processes are cumbersome and time consuming compared to familiar operational decision making. The AF, along with DoD and the other Services, must devote the attention and resources needed to work the system, to anticipate and forestall issues, and to aggressively defend remaining spectrum. The AF must also clean up its acquisition act to ensure that program offices have access to necessary spectrum expertise, use that expertise, comply with policy and directives, and properly balance spectrum considerations in system engineering. Failure to deal with the spectrum situation will be very expensive, both in the loss of capability and in the bills to pay to replace or redesign equipment. In both the short and the long term, a wide variety of technical methods to get more function out of a given bandwidth exist. These must be exploited wherever possible, especially by incentivizing contractors to develop more spectrum-efficient systems. Although much of the problem is beyond the direct control of the AF, the Study Panel urges the leadership to fix those problems that are fixable and to take a proactive leadership role in mustering joint and interagency initiatives, some of which will take years to reach fruition.

APPENDIX A.
TERMS OF REFERENCE

BACKGROUND: The problems of congestion in the RF spectrum, encroachment of commercial and civil uses on spectrum previously allocated to military functions, and difficulty in obtaining spectrum allocation for future systems threaten major cost and operational impacts to the USAF and the DoD. As one example among many, a provision of the 1997 Balanced Budget Act requiring DoD to reallocate for commercial use the seemingly minor amount of 20 MHz of military spectrum below 3 GHz is estimated to cost various Federal agencies over $1B, with *more than half* of that falling on the USAF. Resolution of critical GPS issues has been stymied by frequency allocation concerns. Hundreds of similar instances could be cited.

The Air Force Frequency Management Agency (AFFMA) is responsible for frequency management actions for the USAF and, to a considerable extent, for DoD as a whole. The DoD Joint Spectrum Center provides a variety of technical and operational support to the Services and helps coordinate spectrum management. Both are concerned over the lack of understanding of spectrum problems and the need for aggressive DoD and Service leadership in this area.

The dimensions of this very complex subject include both technical and policy issues, international competition for spectrum, and conflicting interests within the aerospace industry over maintaining military spectrum vs. its use for more lucrative commercial business. Even within USAF, system acquisition programs routinely fail to meet their obligations with respect to identifying and resolving spectrum issues. It's important that USAF leaders at all levels understand these problems and take appropriate actions. Most basic approaches to solutions involve major and expensive changes to move systems to less congested spectral regions. The AFSAB can contribute in this arena by focusing and articulating the issues, exploring possible solutions, and recommending a concrete action plan.

STUDY PRODUCTS: Briefing to SAF/OS & AF/CC in Summer 1999. Publish report Fall 1999.

STUDY CHARTER:

(1) Prepare a concise summary of the frequency management challenge, both today and anticipating emerging systems such as JSF (with its system-of-systems environment) and space based radar.

(2) Meet with representative firms in both defense and non-defense industries (telecommunications, earth observation, public safety, etc.) to gather data on current and projected spectrum requirements and on their strategies for obtaining additional spectrum and more efficiently using currently allocated spectrum.

(3) Identify and assess technical issues such as methods for spectrum re-use, technically defensible thresholds for assured non-interference, migration of functions to millimeter-wave and higher bands, etc.

(4) Identify and assess international spectrum management issues that impact employment of aerospace forces worldwide

(5) Assess impacts to future military system development and modification programs arising from the projected spectrum allocation challenge.

(6) Seek innovative approaches, both technical and spectrum allocation, to mitigate these problems and maximize the assurance of robust, global operability of military forces.

(7) Develop a recommended action plan that addresses:
   (a) Revisions to current USAF spectrum management policy and recommended changes to DoD policy.
   (b) Mechanisms for effective senior leadership oversight of spectrum management status and issues.
   (c) Interaction between USAF and industry to promote mutually beneficial solutions to spectrum problems and minimize industry subversion of military spectrum allocations.
   (d) Measures to ensure system acquisition and modification programs properly and proactively address spectrum management.
   (e) Technology developments and system design features to facilitate migration of military functions to less congested spectral bands.
   (f) Other aspects of improved USAF spectrum management.

APPENDIX B
STUDY PARTICIPANTS

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Dr. John Krieck, JKreik Associates. Ad Hoc Member

Mr. Nelson Pollack, Air Force Frequency Management Agency. Technical Advisor

Lt Col Paul Schubert, Air Force Scientific Advisory Board Secretariat. Executive Officer

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APPENDIX C
TECHNICAL MEANS TO INCREASE EFFICIENCY IN SPECTRUM USE

Over the course of the study, the Panel compiled a list of 17 ways to deconflict competing users and improve the amount of information that can be transferred using a given bandwidth:

1. *Filters on Transmitters*. Steep skirted filters on transmitter outputs reduce the interference with receivers that are tuned to nearby frequencies.

2. *Filters on Receivers*. Receivers can be protected from adjacent channel interference with filters that block energy from adjacent channel transmitters.

3. *Time-Shared Use of a Band*. Two users of the same frequency can be scheduled to operate only when the potential interference source is not present. Such as the case for low power AM stations which turn off their transmitters at night when distant AM stations on the same frequency can be heard over a much larger area due to ionospheric effects.

4. *Orthogonal Waveforms*. Two competing users of the same spectrum can operate simultaneously so long as their waveforms are orthogonal. Examples include TDMA (Time Division Multiple Access) and CDMA (Code Division Multiple Access) waveforms. TDMA waveforms arrange for different users to transmit and receive their particular information in time slots that are interleaved with the time slots allocated to other users. This is a very precise version of time shared use. CDMA allows different users to actually transmit at the same time, but through the use of different codes for different transmitters and special receiver signal processing, different codes to be detected by different receivers in the presence of the other coded waveforms (interfering signals).

5. *Antenna Directivity*. Narrow beams, arrays of small spot beams, and similar pattern management methods can be used to keep transmitter energy away from unintended receivers, and, by the same token, receiver antenna directivity can be used to reject interfering signals by placing an antenna null (or at least reduced antenna gain) in the direction of the source of interference relative to the gain in the direction of the desired signal. This is the case for radars and point-to-point microwave links.

6. *Active Cancellation and Adaptive Processing*. These techniques are similar to antenna directivity except that the reduction in antenna gain in the direction of the interference source is produced computationally (either by analog or digital methods).

7. *Receiver Sensitivity Limits*. Receiver sensitivity limits require that a receiver reject signals below a specific level. This technique is paired with transmitter filters to assure that even when the receiver is close to the transmitter, there is no interference due to out of band emissions from the transmitter (correspondingly, it reduces the cost of transmitter filters when there are a large number of transmitters relative to the number of receivers as is the case with cellular phones).

8. *Transmitter Power Limits*. Transmitter power limits are a symmetric solution to receiver sensitivity limits. By limiting the output power of a transmitter, the range at which it will interfere with a receiver that has a particular out-of-band sensitivity can be reduced.

9. *Altitude Use Limits*. Because higher frequencies propagate better along direct line-of-sight paths while lower frequencies tend to follow the curvature of the earth, height (above ground level) or altitude (above sea level) limits can be imposed on high frequency transmitters to limit the range at which a transmitter can interfere with by a distant receiver. Similarly, a receiver can be kept close to the ground to reduce the extent to which it sees interfering signals from distant transmitters.

10. *Geographic Separation*. Geographic separation can be used to minimize interference between systems due to the reduction in signal strength that is related to distance (either due to atmospheric attenuation or simply due to range).

11. *Real Time Negotiation of Band Occupancy*. It is possible to use real-time negotiation with a master controller to set the frequency, time slot, or code to be used by a particular system for a particular time period. One version of this technique is DAMA (Demand Assigned Multiple Access) which is used to control access to the UHF satellite communications network.

12. *First Use Band Occupancy in Real Time*. First use spectrum occupancy in real-time is less efficient than DAMA at allocating bandwidth but does not require a master controller. However, each transmitter must be able to sense the environment and determine whether it will be interfered with. Airborne radars use this technique to determine if a channel they are about to use is occupied by another signal. When they find that they are about to use a busy channel, they either choose another one, or wait until the channel becomes quiet enough to use.

13. *Interference Tolerance Through Error Detection and Correction*. Interference tolerance through error detection and correction (EDAC) is a common technique to assure low error rates in the presence of noise or interference from other sources. The EDAC coding scheme will be selected to ameliorate the type of interference expected and to yield acceptable end-to-end error rates.

14. *Statistical Band Sharing*. Statistical band sharing allocates traffic to spectrum that is known to be occupied but accepts the associated interference on a statistical basis, much as the Ethernet protocol allows collisions while still getting reliable traffic through.

15. *Polarization Diversity*. Polarization diversity takes advantage of the ability to construct orthogonal waveforms in space as well as in time or frequency. In this case the orthogonality is in polarization, most commonly using vertical and horizontal polarization.

16. *Migration to Millimeter Wave Bands*. Migration to higher and higher frequencies is an approach that is made available by the advance of science and technology. While it is true that some frequencies are not well suited for long range communications due to atmospheric absorption, it is also true that high atmospheric attenuation allows high levels of spectrum reuse over short geographic distances thus making available more spectrum for local use. Unfortunately, the millimeter wave windows at 35 and 94 GHz are already heavily subscribed by non-defense users.

17. *Improved Methods for Demonstrating Non-Interference*. Better tools, both analytical and experimental, for quantifying thresholds and impacts of interference among radio services in a given band would allow better judgments about permitting such sharing.